O'BRIEN & GERE
Landover, Maryland

OPEQUON CREEK CAPACITY STUDY (VIRGINIA)

Completed for the Frederick-Winchester Service Authority

March 2005

OBAG0110

HydroQual

Environmental Engineers & Scientists

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EXECUTIVE SUMMARY

The primary objective of the Opequon Creek Capacity Study is to develop a technically defensible water quality model of Opequon Creek to support subsequent wastewater master planning by the Frederick-Winchester Service Authority (FWSA), County and City. As part of the Opequon Creek Capacity Study, field programs were designed and performed to gather current water quality information in the Opequon Creek watershed in addition to the development of an updated water quality model (DIURNAL) for the creek. This water quality model is similar to the USEPA supported QUAL2E model and has been applied for a number of point source permitting projects with the Virginia Department of Environmental Quality (VDEQ). HydroQual, Inc. (HQI), O'Brien & Gere Engineers, Inc. (OBG) and the Academy of Natural Sciences of Philadelphia (ANSP) conducted two, approximately 1-week long field surveys of Opequon Creek and major tributaries to the creek for the FWSA in the fall of 2004. Finally, the updated water quality model of the creek was used to determine the assimilative capacity of the creek to assist in point source permitting.

The following conclusions are the result of the field program and model development effort.

- The two field surveys of the creek gathered information relating to water quality including algal effects, geometry and travel time to support development of an updated water quality model of the creek. During these surveys, a number of spring fed tributaries were encountered (e.g., Dry Marsh Run) that have significant flow somewhat independent of runoff conditions in addition to being cooler than the creek with different water quality characteristics.
- The water quality data collected included measurements of dissolved oxygen (DO), BOD, suspended solids (SS), temperature, conductivity, pH, nitrogen, phosphorus and chlorophyll-a. DO levels during these surveys were all greater than 6 mg/L (above the daily average DO standard of 5 mg/L). Continuous data recorders were installed at six locations in the creek and indicated large daily diurnal DO swings (2-10 mg/L) with minimum levels always greater than 6 mg/L. TN levels were less than 7 mg/L, TP less than 0.8 mg/L and chlorophyll-a levels less than 2 mg/L. In general, all nutrient levels decreased in the downstream direction.
- Creek geometry and travel time information was also obtained throughout the creek, which provided a significant upgrade in the understanding of the creek's physical characteristics.
- The water quality model (DIURNAL) was chosen to represent Opequon Creek since it contains the necessary structure to simulate diurnal variation of DO in addition to the various parameters of concern (i.e., carbonaceous BOD and nitrogen). In addition, the DIURNAL model was used to complete water quality modeling for the Opequon Wastewater Reclamation Facility (OWRF) (HydroQual, 1997) and for permitting with

VDEQ. This upgraded model of the creek will be used for continued permitting of the Parkins Mills Wastewater Treatment Facility (PMWWTF) (permit reopening), the OWRF (permit reapplication) and the County Landfill.

- Using the data collected in 2004, the DIURNAL model was developed to represent Opequon Creek from just upstream of the PMWWTF to approximately 26 miles downstream. The model calibration is completed to develop a model that best represents the available data and was calibrated to the geometry data (depth, width, cross-sectional area, velocity and flow) and then to the water quality data (organic, ammonia and nitrite plus nitrate nitrogen, conductivity, CBODu and DO).
- In general, the DIURNAL model output compares well with observed data for all parameters over the length of the creek analyzed and specifically, the model represents the measured CBODu and DO data very well. The model comparison to the observed data resulted in a successful calibrated model that can be used to assess the assimilative capacity of the creek.
- The calibrated water quality model of Opequon Creek provides a tool to determine the assimilative capacity of the creek for point source permitting of the PMWWTF, OWRF and County Landfill in addition to considering the new discharge from the Northern Wastewater Reclamation Facility (NWRF). The calibrated model was used for these water quality projection analyses with the creek flow set at the 7Q10 low-flow and at summer creek temperatures.
- For all of the discharge cases analyzed under both cloudy and sunny conditions, the daily average creek DO is always greater than the 5 mg/L State DO standard at the critical summer, low-flow creek conditions. Also, the daily minimum DO for both the cloudy and sunny conditions is always greater than the 4 mg/L State DO standard for all discharge cases. These water quality projections included discharges from the PMWWTF, County Landfill, OWRF and the potential new discharge from the NWRF.

SECTION 1

INTRODUCTION

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SECTION 1

INTRODUCTION

The primary objective of the Opequon Creek Capacity Study is to develop a technically defensible water quality model of Opequon Creek to support subsequent wastewater master planning by the Frederick-Winchester Service Authority (FWSA), County and City. Development of the water quality model was based on all available data with particular emphasis placed on the 2004 data because it best represents the current environmental conditions in the creek. The water quality modeling is intended to help answer the basic question of what is the assimilative capacity of Opequon Creek for receiving wastewater effluent at different treatment levels and locations in the watershed to optimize the assimilative capacity while maintaining water quality.

FWSA owns and the City of Winchester operates the Opequon Water Reclamation Facility (OWRF), which is currently required to achieve biological nutrient removal (BNR) with seasonal limits for other parameters. FWSA owns and Frederick County Sanitation Authority operates the Parkins Mills Wastewater Treatment Facility (PMWWTF), which is currently required to achieve Secondary Treatment – Nitrification. There are other point and nonpoint source discharges within the watershed not managed by the FWSA. These dischargers include the Frederick County Landfill point source discharge and various nonpoint source tributary and direct runoff loadings.

As part of the Opequon Creek Capacity Study, field programs were designed and performed to gather current water quality information in the Opequon Creek watershed in addition to the development of an updated water quality model for the creek. The updated water quality model includes the following parameters and associated transformation processes (kinetics): CBOD, DO, organic nitrogen, ammonia nitrogen, nitrite plus nitrate nitrogen and conductivity (conservative tracer). The steady-state creek model DIURNAL was used because it can represent all of these parameters and processes in addition to allowing for diurnal DO calculations to be performed. This water quality model is similar to the USEPA supported QUAL2E model and has been applied for a number of point source permitting projects in Virginia. The DIURNAL model was calibrated and applied to Jackson River from Covington to Clifton Forge for Mead-Westvaco and to the Jackson/James River from Clifton Forge to Eagle Rock for the County of Alleghany. Both of these projects were reviewed and approved by the Virginia Department of Environmental Quality (VDEQ) for the development of NPDES effluent permit limits at the Mead-Westvaco facility and for a proposed wastewater treatment plant for the Alleghany County Department of Public Works.

The field programs were specifically designed to support development of the updated water quality model for the creek. The remainder of this report presents the results from the field program, model development and various water quality projection analyses to investigate potential discharge options for the FWSA as part of NPDES permitting with the VDEQ.

SECTION 2

FIELD PROGRAM

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FIELD PROGRAM

HydroQual, Inc. (HQI), O'Brien & Gere Engineers, Inc. (OBG) and the Academy of Natural Sciences of Philadelphia (ANSP) conducted two, approximately 1-week long field surveys of Opequon Creek and major tributaries to the creek for the FWSA. These surveys were designed to gather information relating to creek water quality including algal effects, geometry, travel time and atmospheric reaeration to support development of an updated water quality model of the creek. The first survey was conducted between October 12th and 14th for the collection of instream water quality and field parameters. The second survey was conducted between November 2nd and 7th for the collection of creek geometry, travel time, atmospheric reaeration information in addition to the deployment of continuous datasondes in the creek to assess algal effects on diurnal DO levels. While the field staff were conducting these surveys, a number of spring fed tributaries were encountered (e.g., Dry Marsh Run) that have significant flow somewhat independent of runoff conditions in addition to being cooler than the creek with different water quality characteristics.

During the second survey a significant rain event occurred on November 4th in which creek flows varied substantially. Although there was a rain event during the second survey, this survey was planned to collect other creek information and not water quality data to describe conditions in the creek. The installation of the continuous datasondes during the second survey actually provided valuable information regarding daily DO variation before, during and after the rain event. Due to a number of hurricanes passing through the area in September the creek surveys were delayed somewhat and ideal summer, low-flow conditions were not captured. In spite of the unusual hurricane season in September, the creek water quality survey was completed at relatively steady low-flow conditions. The hydrographs in Opequon Creek near the USGS Berryville gage (# 01615000) and Stephens City gage (# 01614830) are presented in Figures 1a (log-scale) and 1b (arithmetic-scale) for September through November that show the three hurricane events in September with the two survey periods indicated by the shaded areas.

In order to provide good coverage of the creek in the study area, 19 creek sampling stations and 7 tributary stations were sampled for a variety of water quality parameters. The study area ranged from just upstream of the PMWWTF near the Route 522 crossing of the creek to approximately 25 miles downstream near the Route 51 crossing of the creek by Middleway (WV). The station locations in the study area are presented in Figure 2 and tabulated in Table 1. In addition, 2 effluent samples were also collected from the PMWWTF and the OWRF. These field surveys were aimed at measuring ambient water quality in the creek and tributaries, atmospheric oxygen reaeration capacity, travel time through the creek and creek geometry. The data collected were used to develop a mathematical water quality model (DIURNAL) of Opequon Creek to assist

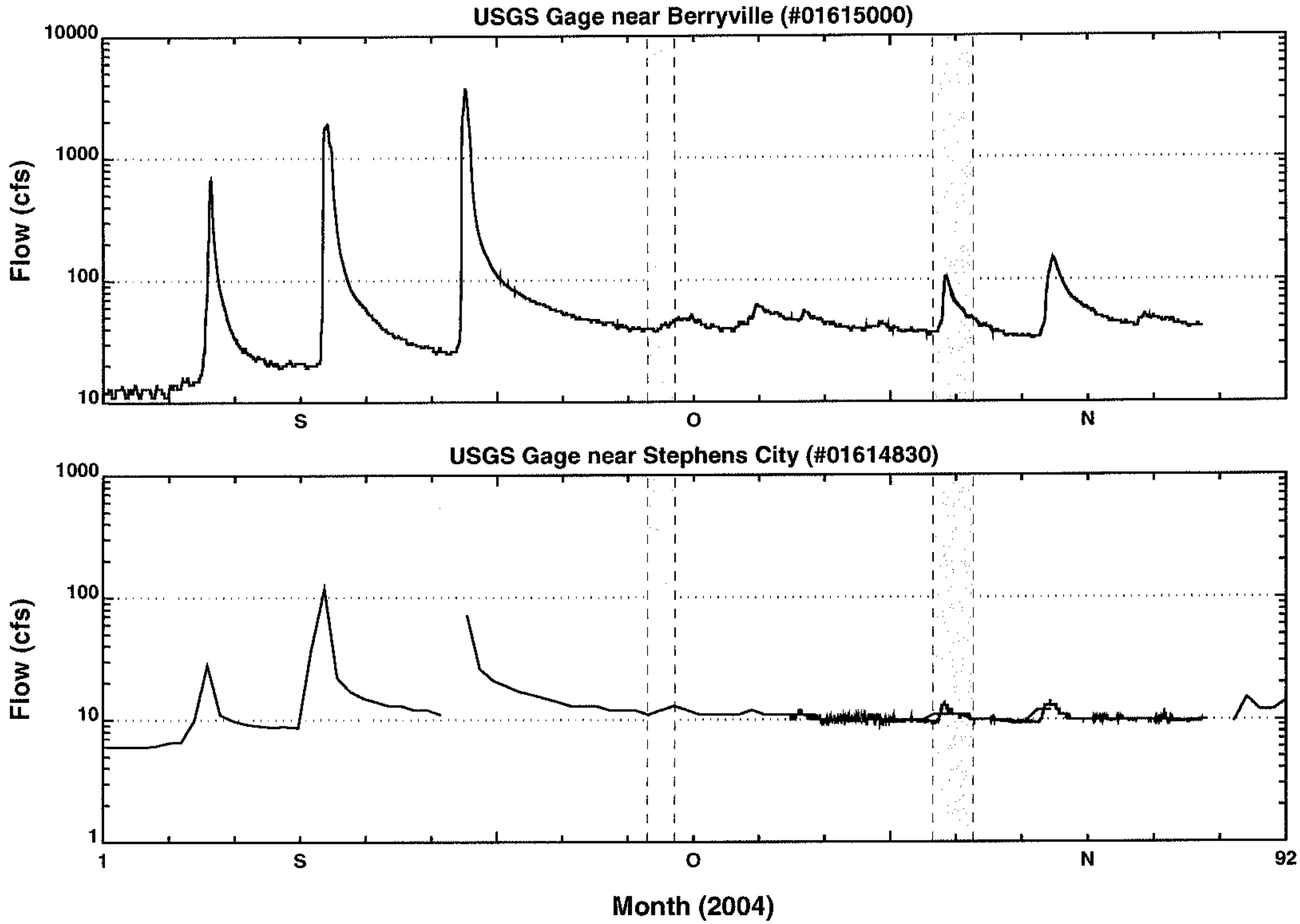


Figure 1a. Opequon Creek Survey USGS Stream Flows (9-11/2004) - Log-Scale

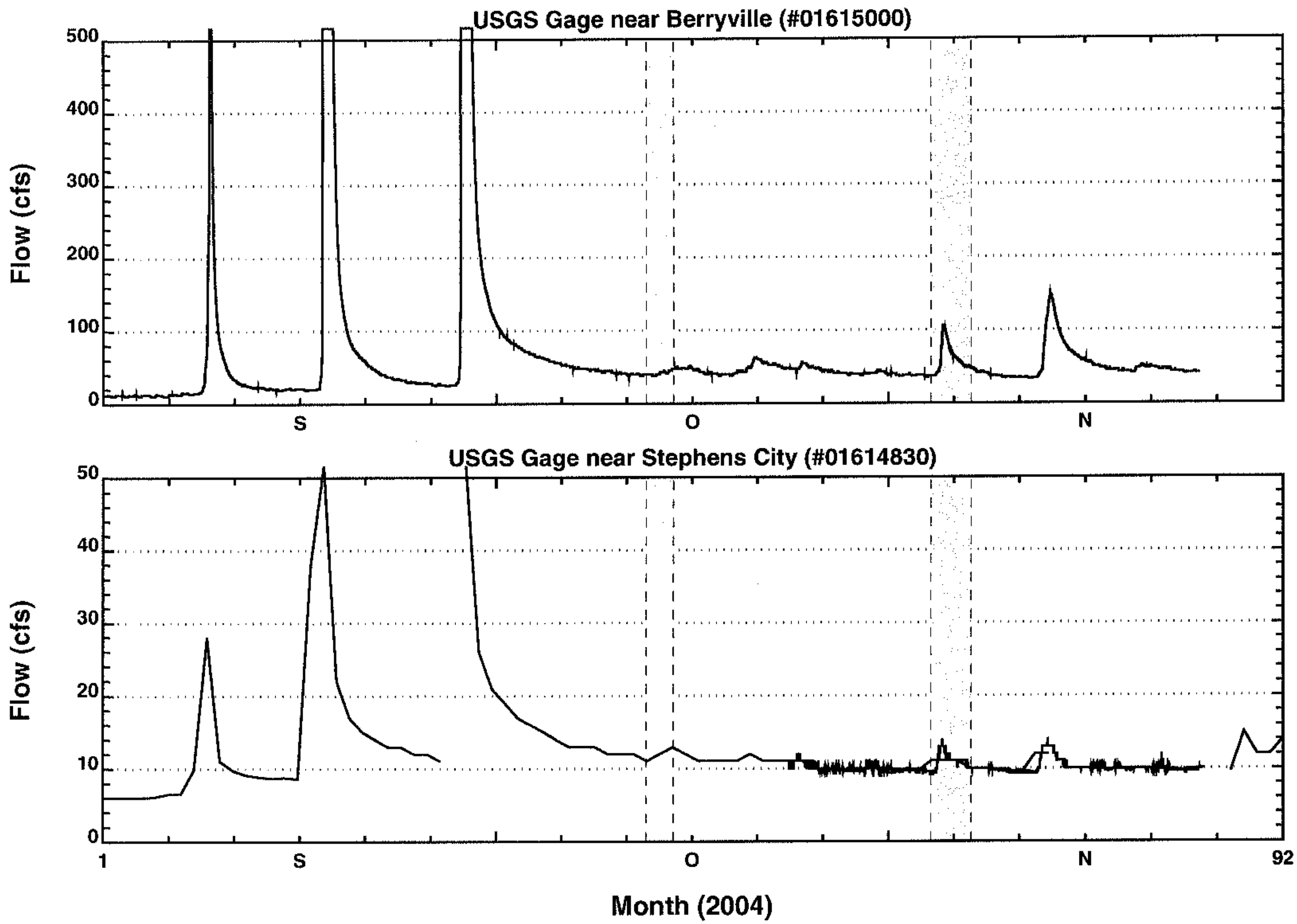


Figure 1b. Opequon Creek Survey USGS Stream Flows (9-11/2004) - Arithmetic-Scale

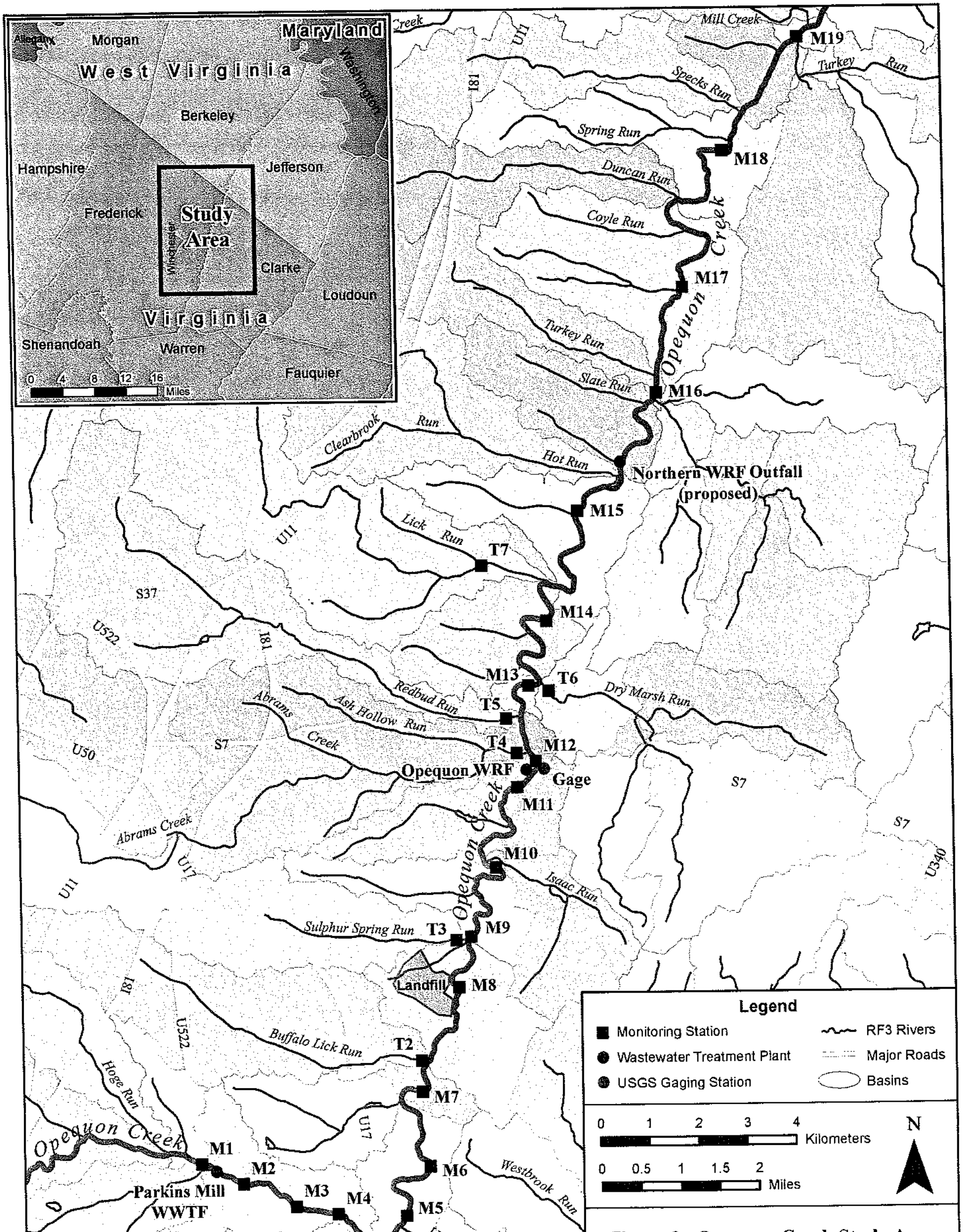


Figure 2. Opequon Creek Study Area

the FWSA in permitting of the PMWWTF and the OWRF with the VDEQ and also for overall watershed wastewater facilities planning in the Frederick-Winchester area.

Table 1. Monitoring Station Locations

Station	Description
M1	Above PMWWTF
M2	Route 522 crossing
M3	Private property access # 1
M4	Private property access # 2
M5	Route 50/17 crossing
M6	Route 644 crossing
M7	Route 723 crossing
M8	Near landfill (below discharge)
M9	Route 655 crossing
M10	Route 657 crossing
M11	Above OWRF
M12	Below OWRF (near Route 7 crossing)
M13	Route 664 crossing
M14	Route 660 crossing
M15	Route 761 crossing
M16	Route 672 crossing
M17	Route 667 crossing (Old Braddock Road – Carters Ford)
M18	Ford above Silver Spring Run
M19	Ford above Mill Creek near Middleway
T1	Wrights Run, Route 642 crossing
T2	Buffalo Lick Run, Route 723 crossing
T3	Sulphur Spring, road crossing off of Route 655
T4	Abrams Creek, Route 659 crossing
T5	Redbud Run, Route 659 crossing
T6	Dry Marsh Run, Route 645 crossing
T7	Lick Run, Route 664/761 crossing

The reaeration and time of travel study was conducted in three reaches of the creek and samples collected for sodium bromide (conservative tracer) and propane. Unfortunately when the propane samples were analyzed at the ANSP laboratory, upstream levels were lower than downstream levels (opposite of what should occur) and subsequent analyses at another laboratory were all reported at or less than the detection limit. Therefore, determination of creek atmospheric reaeration rates was not possible although the time of travel results using the bromide data were successful and used to determine creek velocities and flows. Although estimates of reaeration were not possible, a widely used and accepted reaeration equation will be used (the Tsivoglou-Wallace formulation), which is applicable to shallow, fast moving streams. In addition, the Tsivoglou-Wallace formulation has been used on previous modeling studies of the creek. Since the datasondes were installed, the measured continuous DO data can be used to infer the reaeration rates in the creek. That is, the diurnal DO pattern measured is a function of the reaeration rate and will be used to verify the reaeration rates calculated with the Tsivoglou-Wallace reaeration formulation.

2.1 WATER QUALITY

The instream water quality surveys of the creek were completed on October 13th (PM) and October 14th (AM) by HQI, OBG and ANSP staff. Samples were collected in 4-liter containers either from bridge overpasses (if creek access was not possible) or directly in the creek and tributaries. The sampling was completed by three sampling teams to allow coverage of the creek study area in a relatively synoptic manner (i.e., sampling throughout the creek occurring roughly over the same period). The water samples collected were analyzed for total kjeldahl nitrogen (TKN), ammonia nitrogen (NH3), nitrite plus nitrate nitrogen (NO2+NO3), total phosphorus (TP), orthophosphate (PO4), total suspended solids (TSS), volatile suspended solids (VSS), chlorophyll-a, 5-day biochemical oxygen demand (BOD5) and long term BOD (LTBOD) at the ANSP laboratory. In addition, direct field measurement of creek and tributary dissolved oxygen (DO), temperature, conductivity and pH were completed using a portable field meter.

The water quality data collected are presented in Figures 3 and 4 as a function of stream length for DO, BOD5, ultimate CBOD (CBODu), VSS, TSS, temperature, conductivity, pH, TKN, NH3, NO2+NO3, TP, PO4 and chlorophyll-a. Milepoint 0 is where the PMWWTF discharges to the creek and milepoint 12 where the OWRF discharges to the creek. DO levels during these surveys were all greater than 6 mg/L (above the DO standard of 5 mg/L) with water temperatures between 12 and 15°C. The DO saturation level at these water temperatures ranges from 10.1 to 10.8 mg/L. Slight increases in temperature, conductivity and CBOD were present in the data below the PMWWTF and OWRF. Also a slight decrease and recovery in DO below the OWRF was present in the data. The nutrient data also show an increase in upstream levels below the PMWWTF and a decrease from upstream levels below the OWRF. TKN levels were less than 0.5 mg/L, NH3 levels less than 0.015 mg/L, NO2+NO3 levels less than 6 mg/L, TP less than 0.8 mg/L, PO4 less than 0.75 mg/L and chlorophyll-a levels less than 2 mg/L. In general, all nutrient levels decreased in the downstream direction, except for NH3, with relatively constant chlorophyll-a levels. The relatively constant NH3 levels in the creek may be a function of the low levels (<0.02 mg/L) or other sources to the creek. Tables of the water quality data collected on 10/13-14/2004 are presented in Appendix 1.

It is interesting to note that the tributary water quality varied throughout the creek. For example, the first two monitored tributaries (Wrights Run and Buffalo Lick Run) had different water quality than the remaining monitored tributaries (Sulphur Spring, Abrams Creek, Redbud Run, Dry

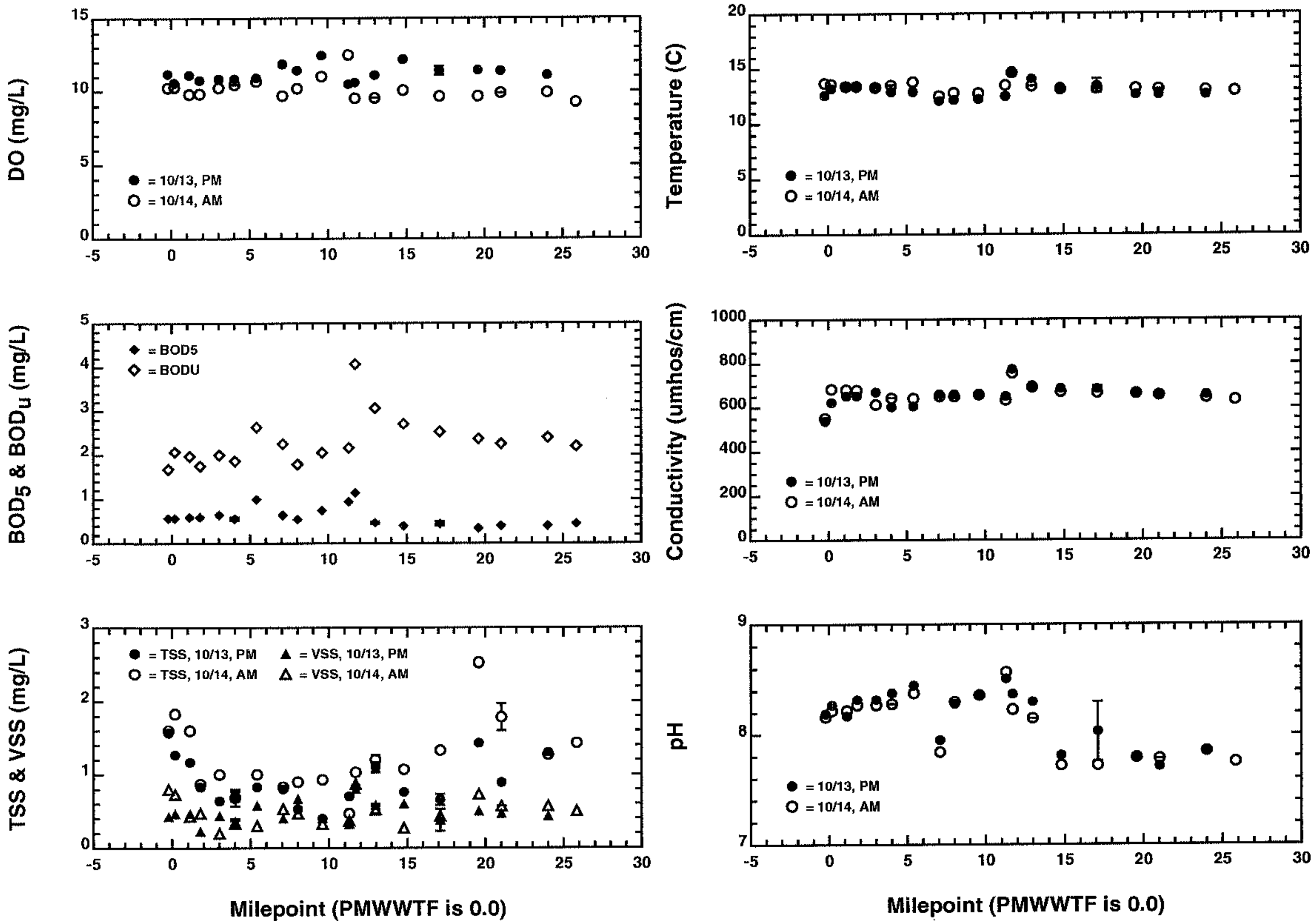


Figure 3. Opequon Creek Water Quality Data for the 10/13-14/2004 Survey

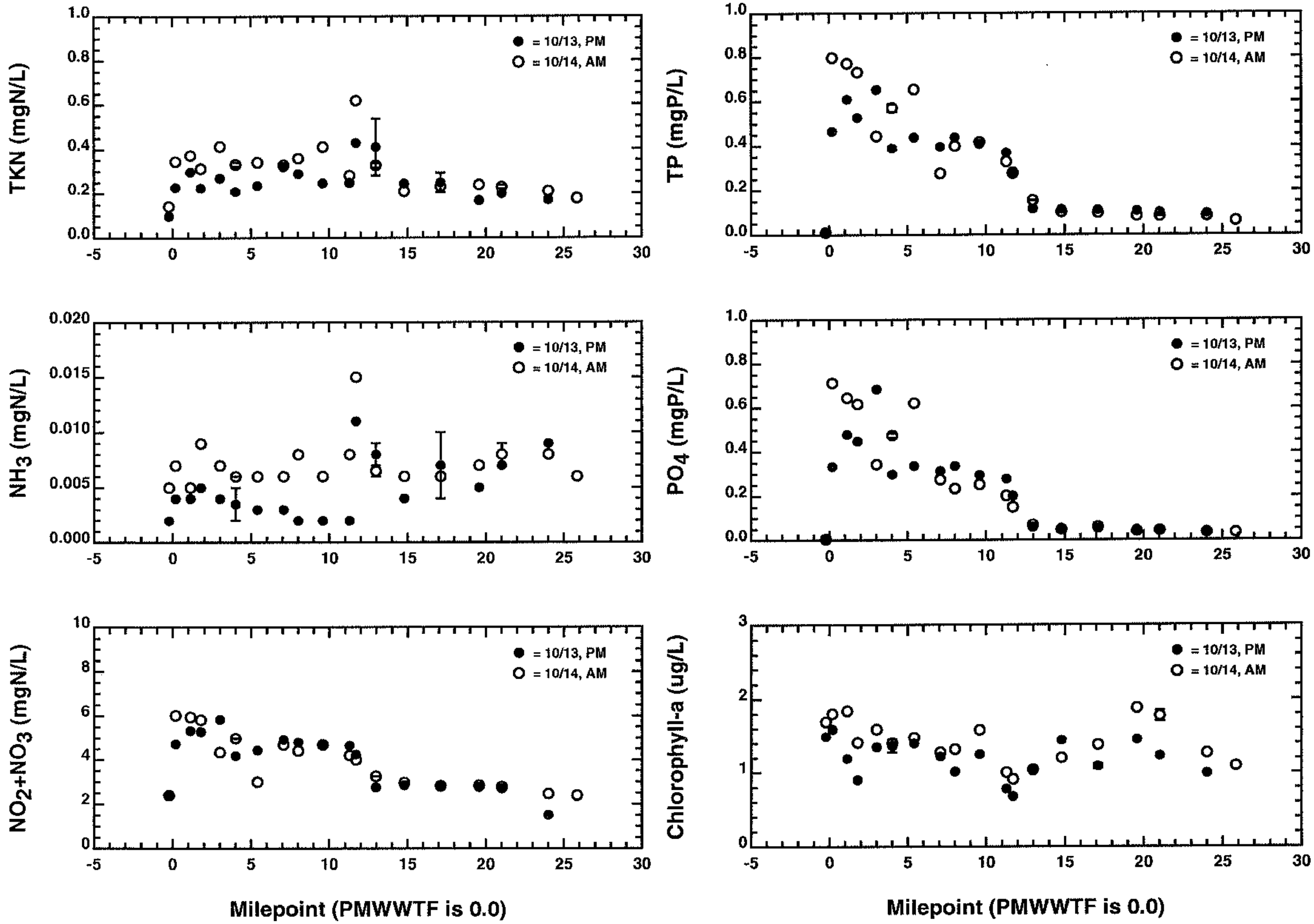


Figure 4. Opequon Creek Water Quality Data for the 10/13-14/2004 Survey

Marsh Run and Lick Run). The first two tributaries had lower conductivity levels than the remaining tributaries (529 vs. 606 mmhos/cm), higher DO (11.6 vs. 9.8 mg/L), and lower NO2+NO3 (0.1 vs. 1.8 mg/L) that may indicate that the first two tributaries may be more dominated by surface runoff and the remaining ones dominated by groundwater (spring fed).

2.2 LONG TERM BOD (LTBOD)

In order to determine the ultimate oxygen demand of a water sample, LTBOD studies were completed on the creek, tributary and effluent samples on October 13th. These studies involve incubating a water sample for an extended period of time (in this case 60 days) and monitoring the DO depletion in a BOD bottle throughout the test. The resulting DO data is then used to calculate BOD versus time and a non-linear regression is performed on the data to determine the ultimate CBOD (CBODu) and the bottle CBOD oxidation rate. It should be noted that the bottle CBOD oxidation rate is not necessarily the stream oxidation rate and depends on the size of the stream. In deep rivers the bottle rate may be a good representation of CBOD oxidation in the receiving water but in a shallow stream it is not. This is because the shallow stream has a large percentage of the water volume in contact with the stream bed where bacteria are more abundant than in the water column, which tends to act like a trickling filter in a WWTP resulting in higher instream CBOD oxidation rates. A trickling filter in a WWTP passes wastewater over a media with attached bacteria to allow greater water contact with the media similar to what is occurring in the shallow creek.

Figures 5 through 9 present the LTBOD data and resulting CBODu and bottle oxidation rate (Kd) determined from a non-linear regression of the data using the following equation:

$$BOD = BOD_u \left(1 - e^{-K_d \times time}\right) \tag{1}$$

Since the DIURNAL model requires input of CBODu, the results from the LTBOD studies will be used to develop CBODu inputs for the model. Another piece of information that results from the LTBOD studies is the ratio of CBODu/BOD5. Based on the LTBOD data, the CBODu/BOD5 ratio for the creek samples averaged 4.11 (2.28-6.82), for the tributaries averaged 5.82 (2.88-8.25), for the PMWWTF was 5.14 and for the OWRF was 4.77. The ranges of these ratios are typical for the creek, PMWWTF and OWRF effluent. The previous effluent CBODu/BOD5 ratio used for the creek modeling was 3 and no based on LTBOD studies but rather general municipal effluent characteristics. These CBODu/BOD5 ratios will be used for water quality projections when converting model input CBODu to BOD5.

2.3 CONTINUOUS FIELD DATA

In order to define the DO concentrations in the creek throughout the day, a number of continuous datasonde recorders were installed at 6 locations in the creek between November 2nd and 7th. The installation stations were M3, M6, M8, M10, M13 and M15 and the datasondes

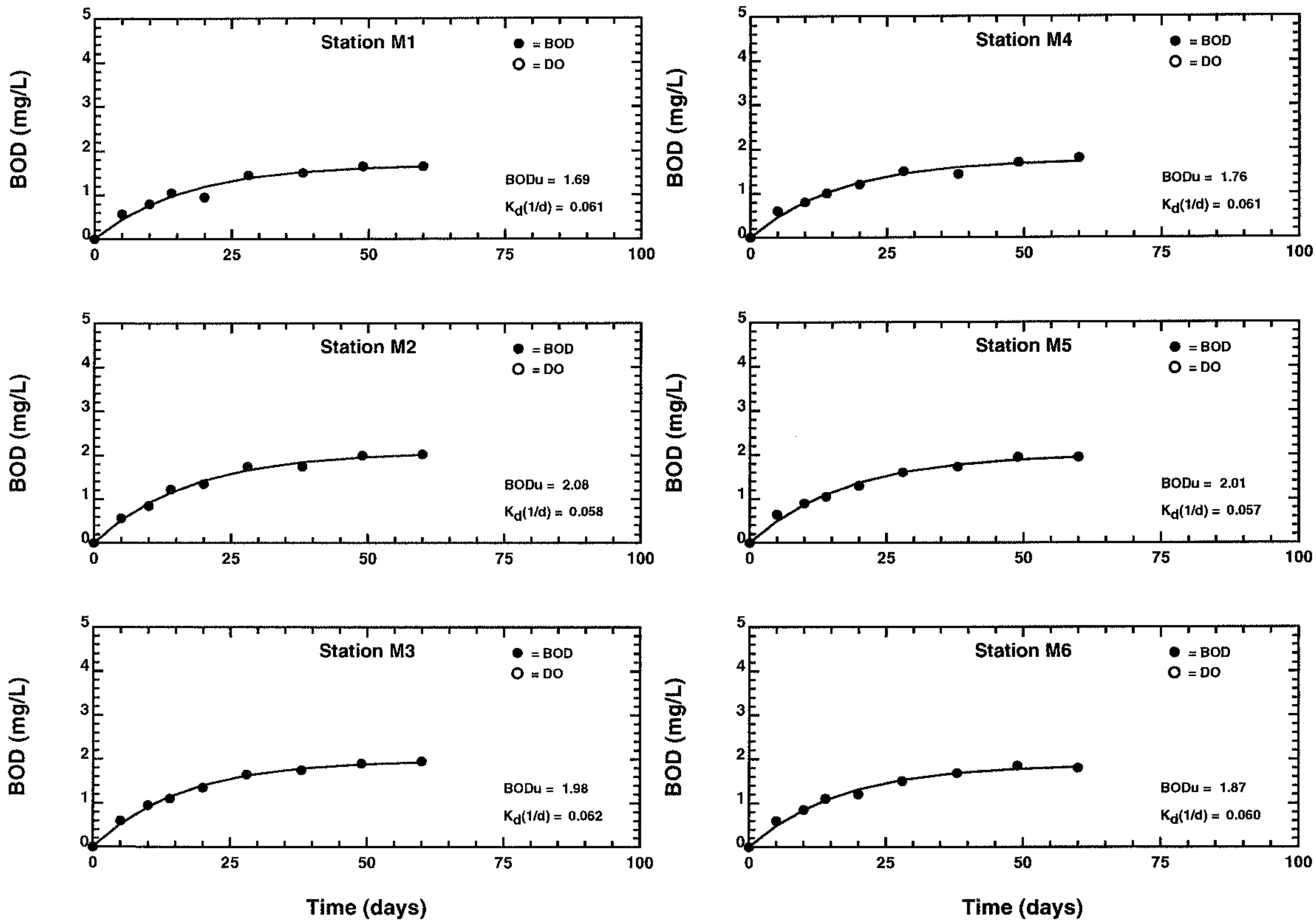


Figure 5. Opequon Creek LTBOD Data for the 10/13/2004 Survey

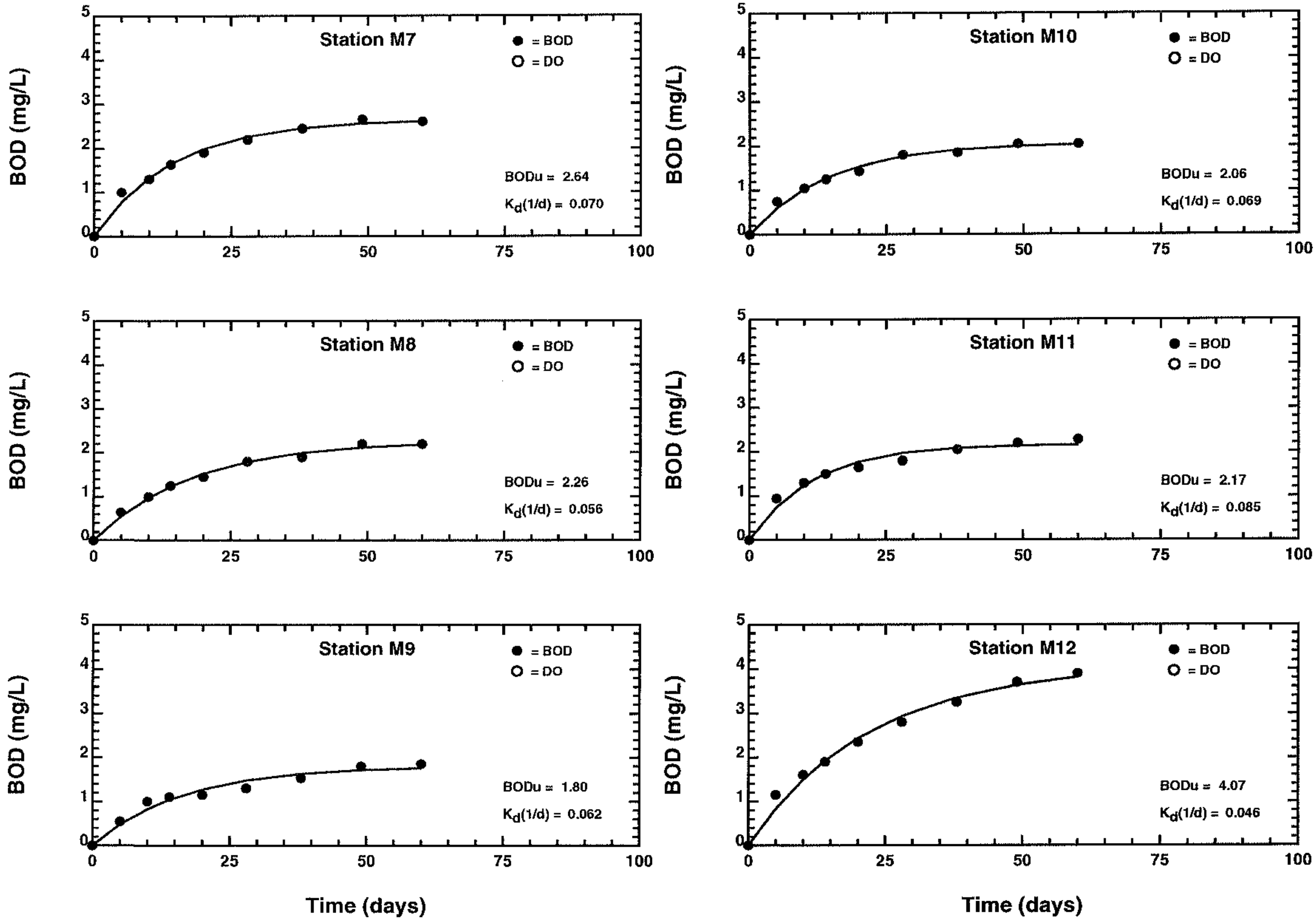


Figure 6. Opequon Creek LTBOD Data for the 10/13/2004 Survey

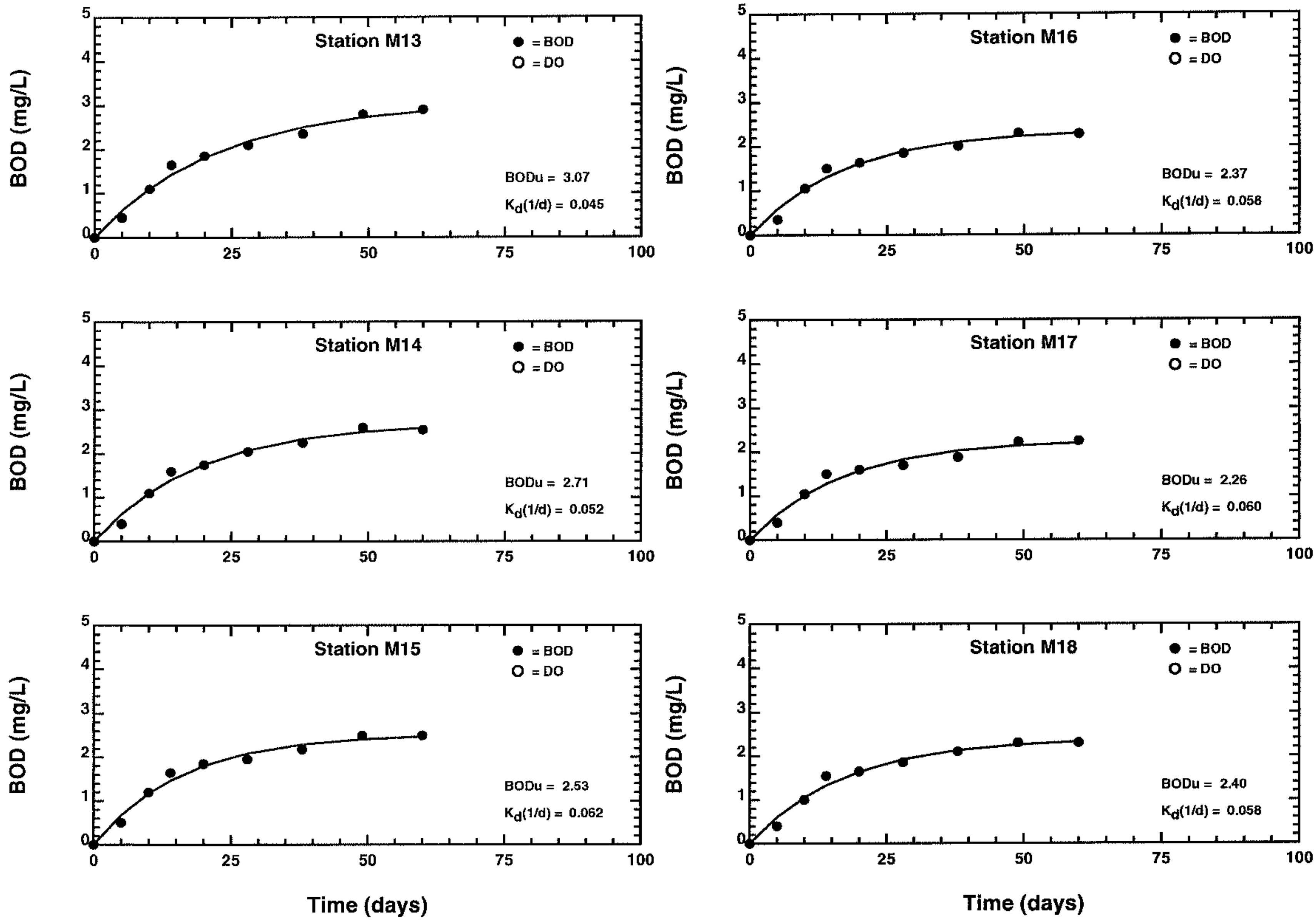


Figure 7. Opequon Creek LTBOD Data for the 10/13/2004 Survey

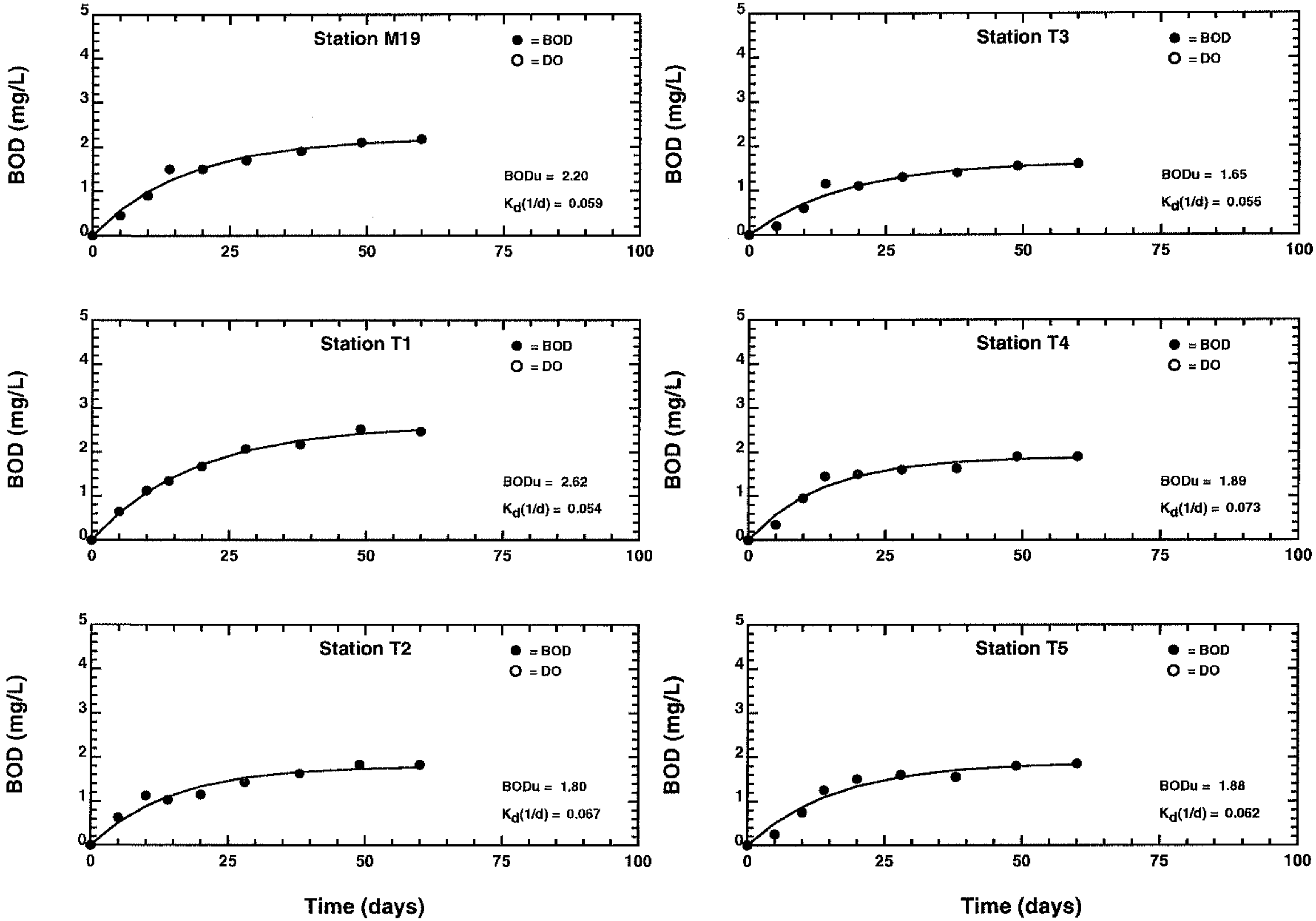


Figure 8. Opequon Creek LTBOD Data for the 10/13/2004 Survey

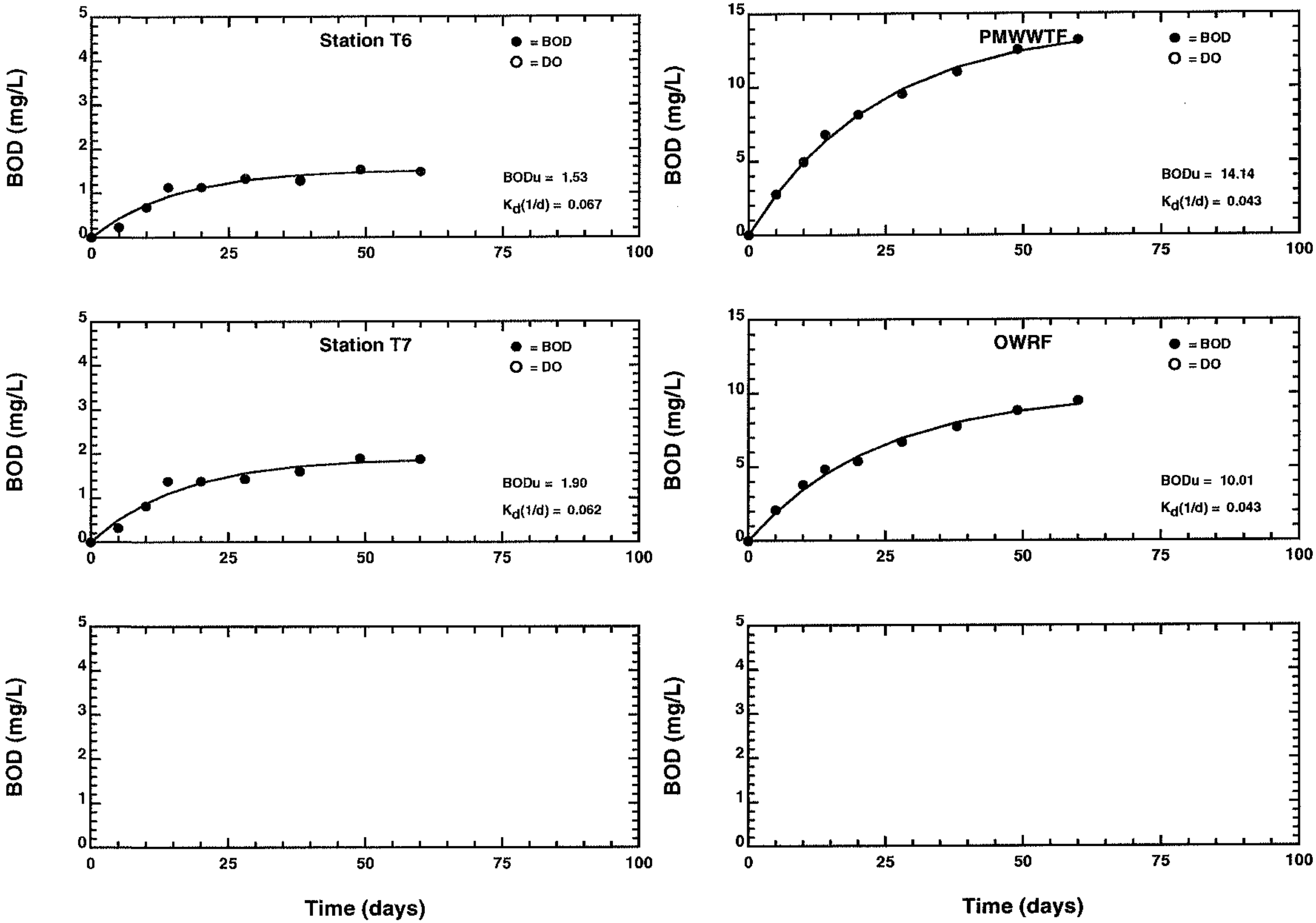


Figure 9. Opequon Creek LTBOD Data for the 10/13/2004 Survey

recorded DO, temperature, pH and conductivity approximately every 15-minutes. Figures 10 through 15 present the continuous data at each station and Figure 16 presents a summary of delta (maximum – minimum), minimum and average DO on each date at each station.

The minimum DO observed (6.7 mg/L) in this dataset occurred on November 3rd at station 10 as did the maximum DO (17.6 mg/L) and the largest delta DO (10.5 mg/L). Station 10 is upstream of the OWRF and downstream of Sulphur Spring Run. These large delta DO values are most likely due to attached algae (rooted aquatic plants or periphyton), as free-floating algae (phytoplankton) typically do not produce such large diurnal swings in DO. As can be seen in Figures 10-16, the rainfall and resulting overcast sky conditions (reduced light) that occurred on November 4th significantly reduced the diurnal DO swings observed at all stations with slight increases in the diurnal DO occurring after the rainfall. It should be noted that the minimum DO levels increased after the rainfall event (Figure 16) due to the decreased diurnal DO activity but daily average DO levels remained relatively constant (except for November 4th). This data highlights the effect that algal oxygen production and respiration have on creek DO levels. That is, average DO levels are relatively similar with or without algal diurnal effects but minimum DO levels are lower with increased algal effects.

2.4 CREEK GEOMETRY

Creek geometry measurements were completed to determine the width, depth and velocity at various cross-sections along the length of the creek. These measurements are used to define the creek geometry for development of the DIURNAL model. The creek cross-section measurements were completed by measuring water depth and velocity across the width of the creek at 1-2 foot increments. These measurements were completed at 29 cross-sections between November 3rd and 6th with velocity measurements taken at 19 of the 29 cross-sections for calculating creek flow. The creek cross-sections are presented in Figures 17 through 22 and as spatial profiles along the creek length in Figure 23.

The creek flow at the Berryville gage during the geometry measurements varied substantially especially on November 4th when the majority of measurements were completed. Creek flow ranged from a minimum of 35 cfs on November 3rd to a maximum of 106 cfs on November 4th. The creek flow increased significantly on November 4th due to a rain event and decreased during November 5th and 6th to a minimum of 48 cfs. The relatively steady creek flows before and after the rain event are approximately 3-4 times higher than average low-flow conditions of about 10 cfs. This unsteady flow during the geometry measurements complicates comparison of measured flows with the measured gage flows. The creek geometry measurements up to station M11 (up to mile 11) were completed roughly before the majority of rainfall occurred and from M13 downstream after the rainfall and increase in creek flow. In general, the calculated upstream flows near the PMWWTF compare well with the Stephens City flow gage but are slightly less than the measured flows at the Berryville flow gage. Given the highly variable flow conditions during the geometry survey, the

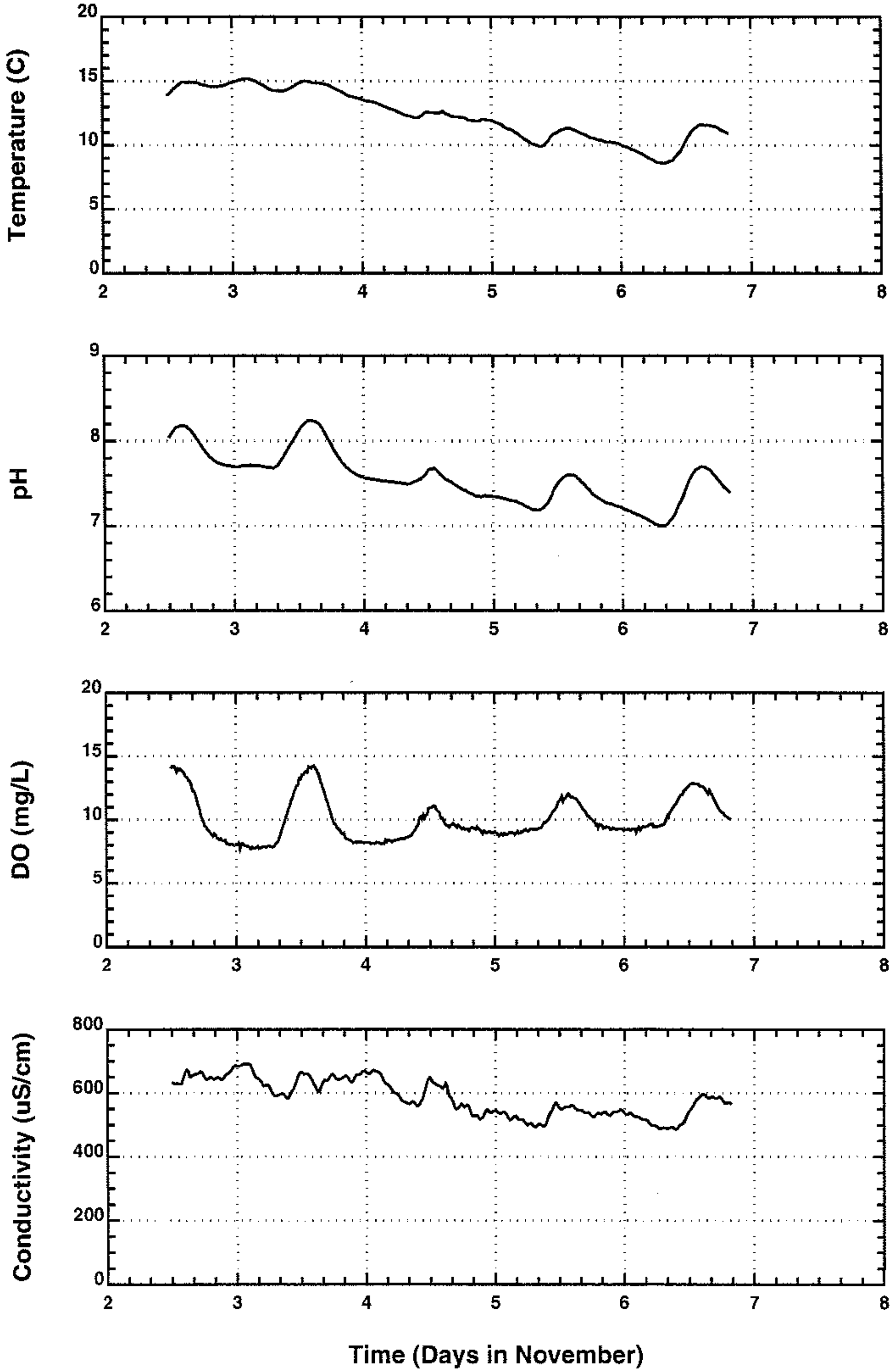


Figure 10. Opequon Creek Continuous Data at Station 3

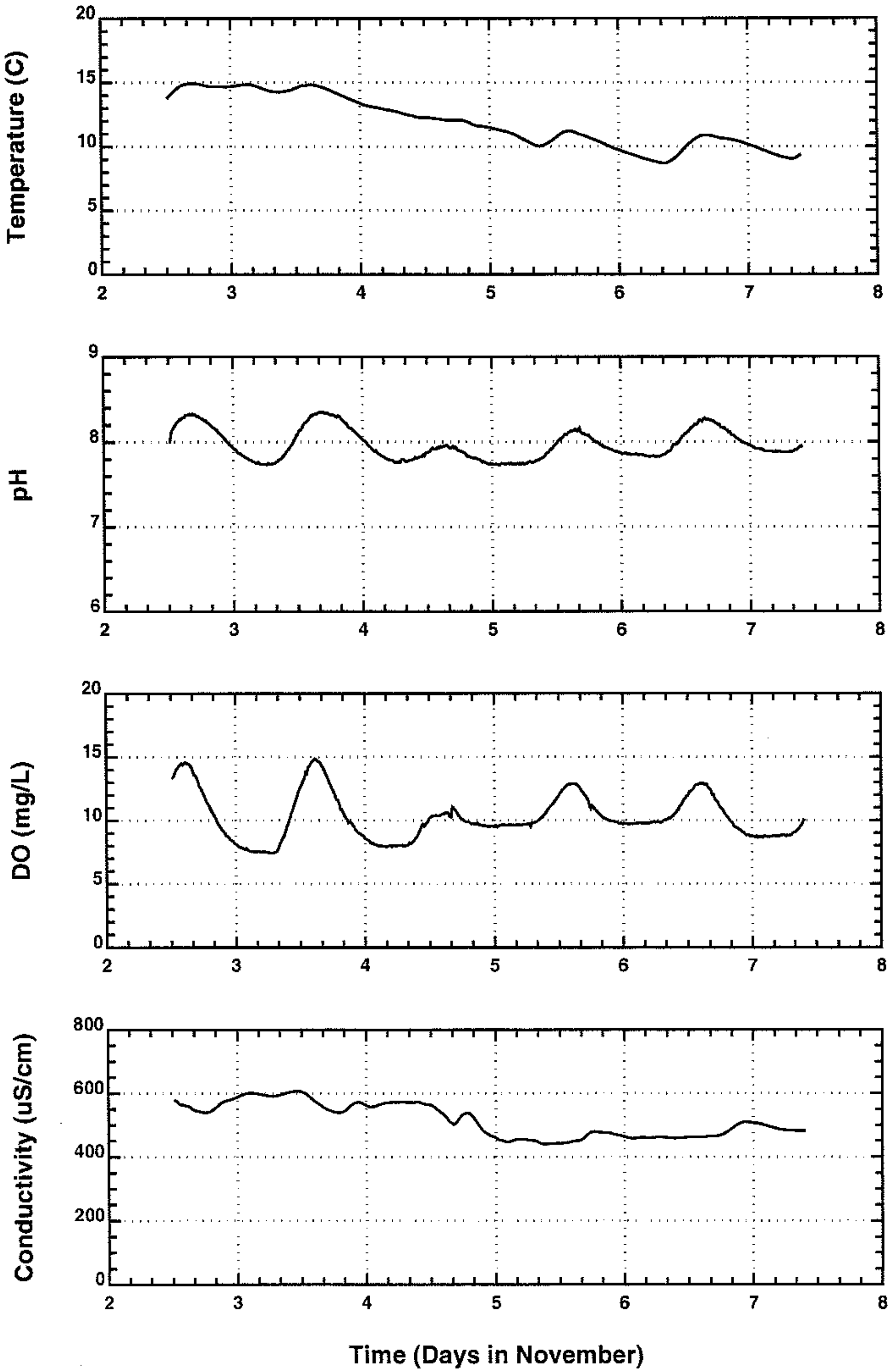


Figure 11. Opequon Creek Continuous Data at Station 6

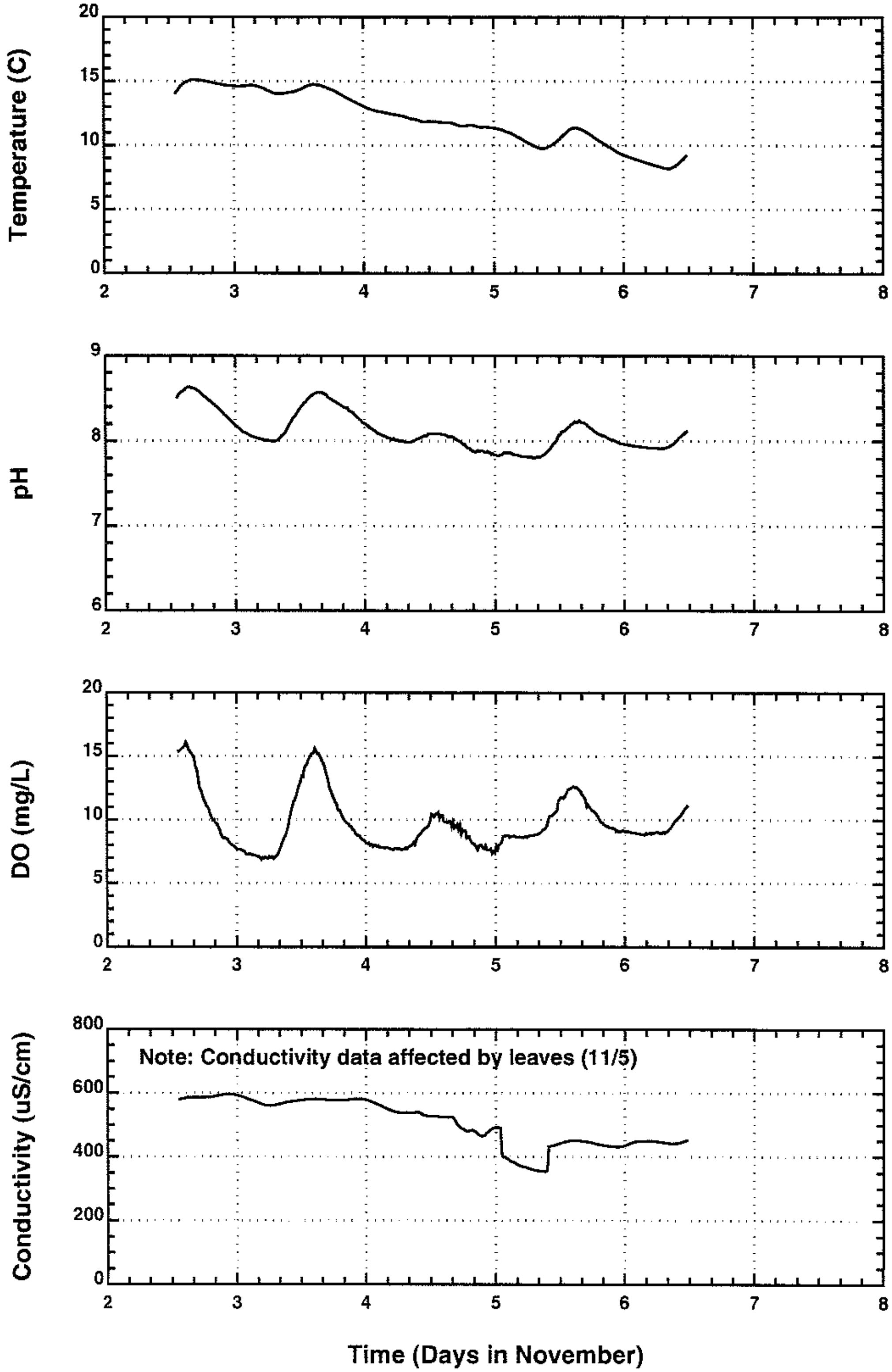


Figure 12. Opequon Creek Continuous Data at Station 8

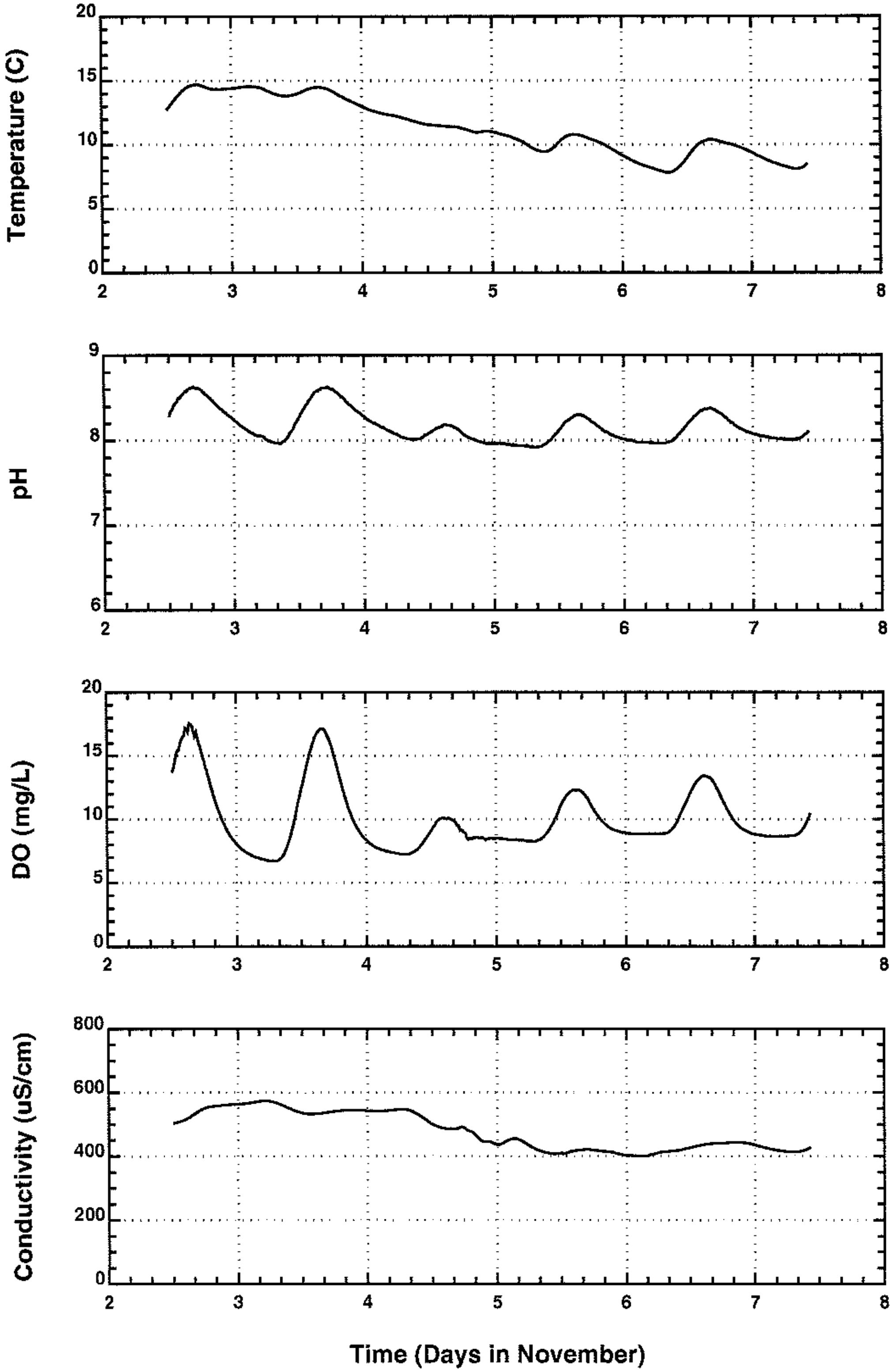


Figure 13. Opequon Creek Continuous Data at Station 10

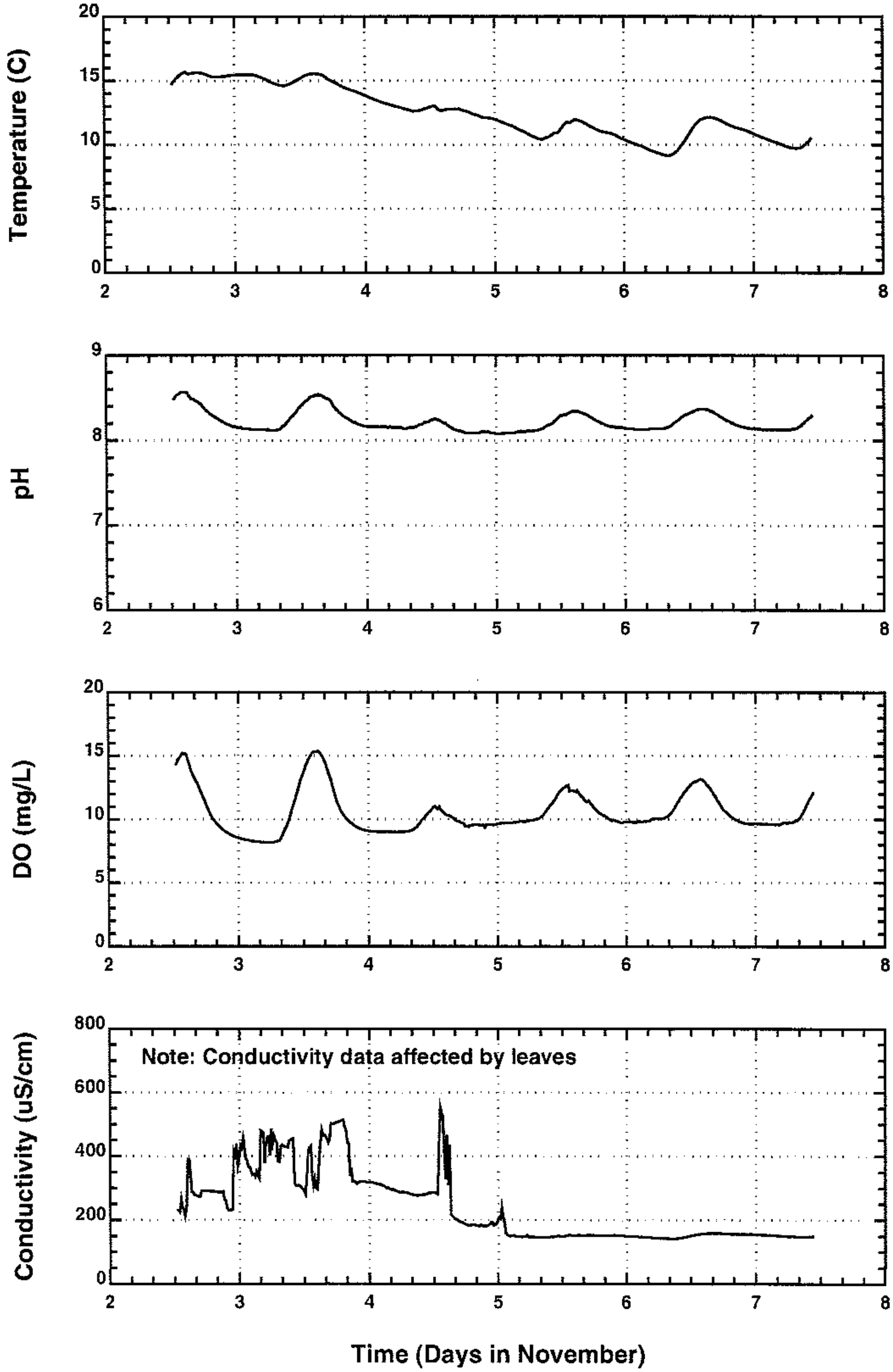


Figure 14. Opequon Creek Continuous Data at Station 13

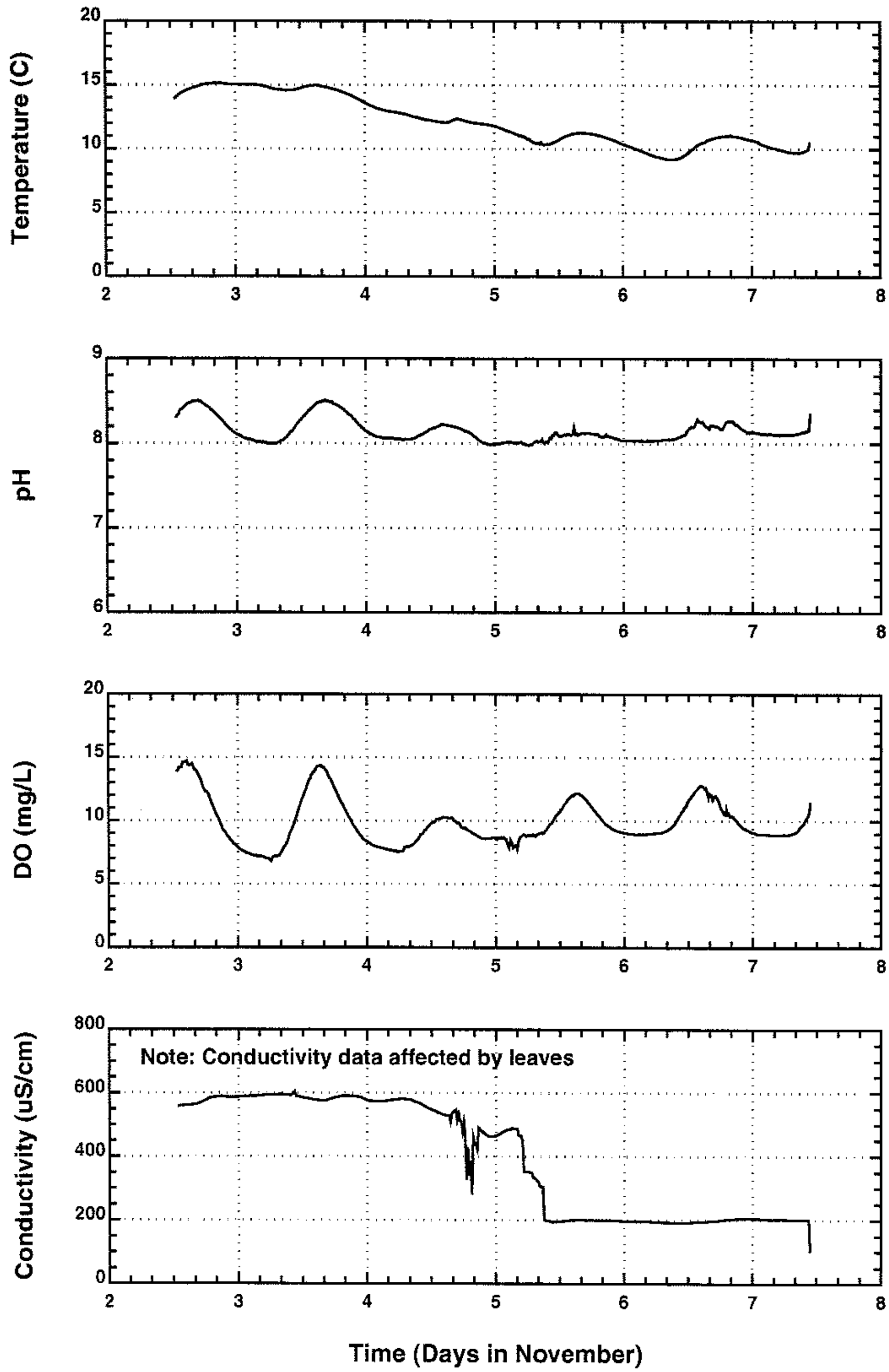


Figure 15. Opequon Creek Continuous Data at Station 15

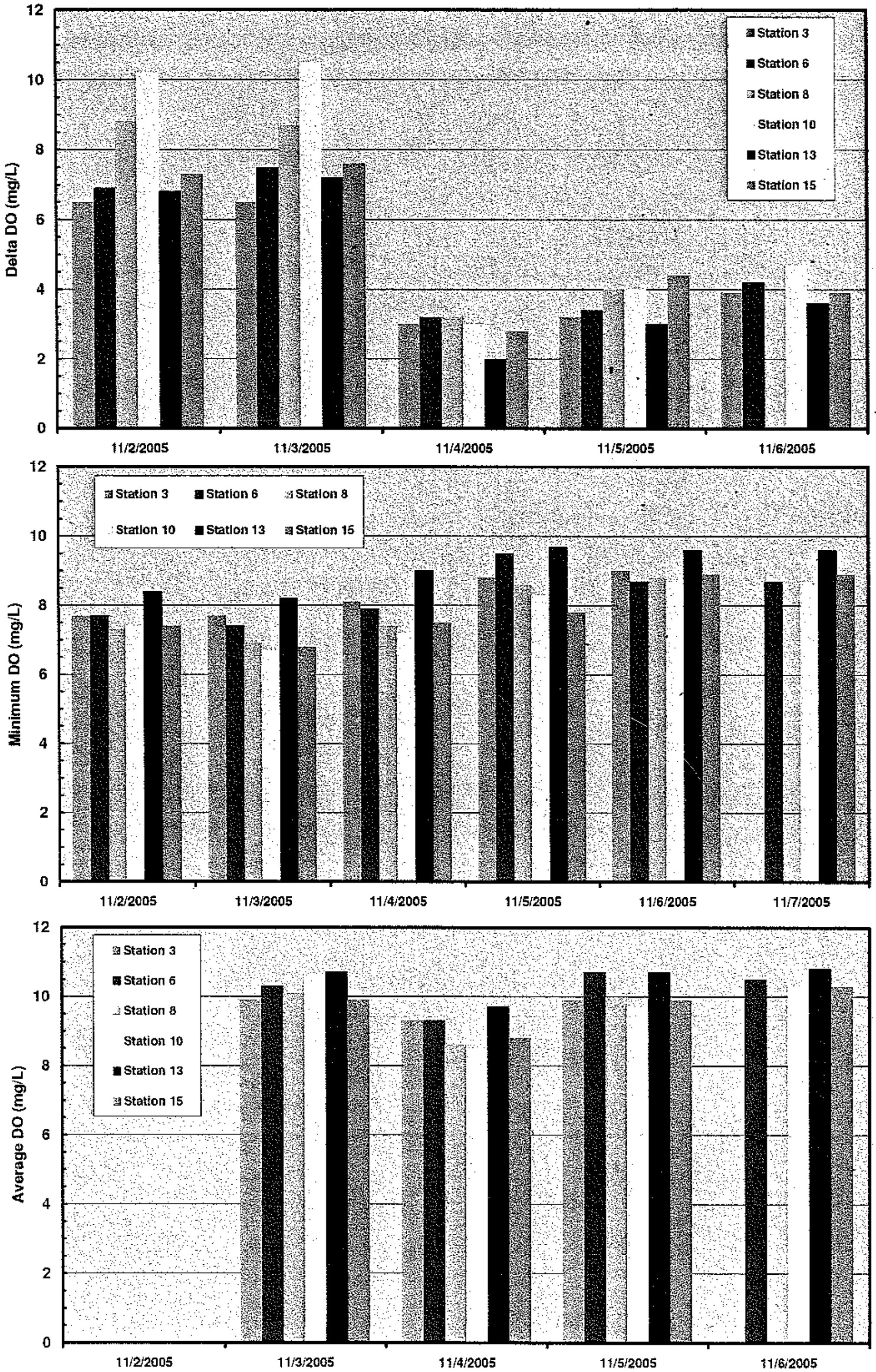


Figure 16. Opequon Creek Continuous DO Data Summary

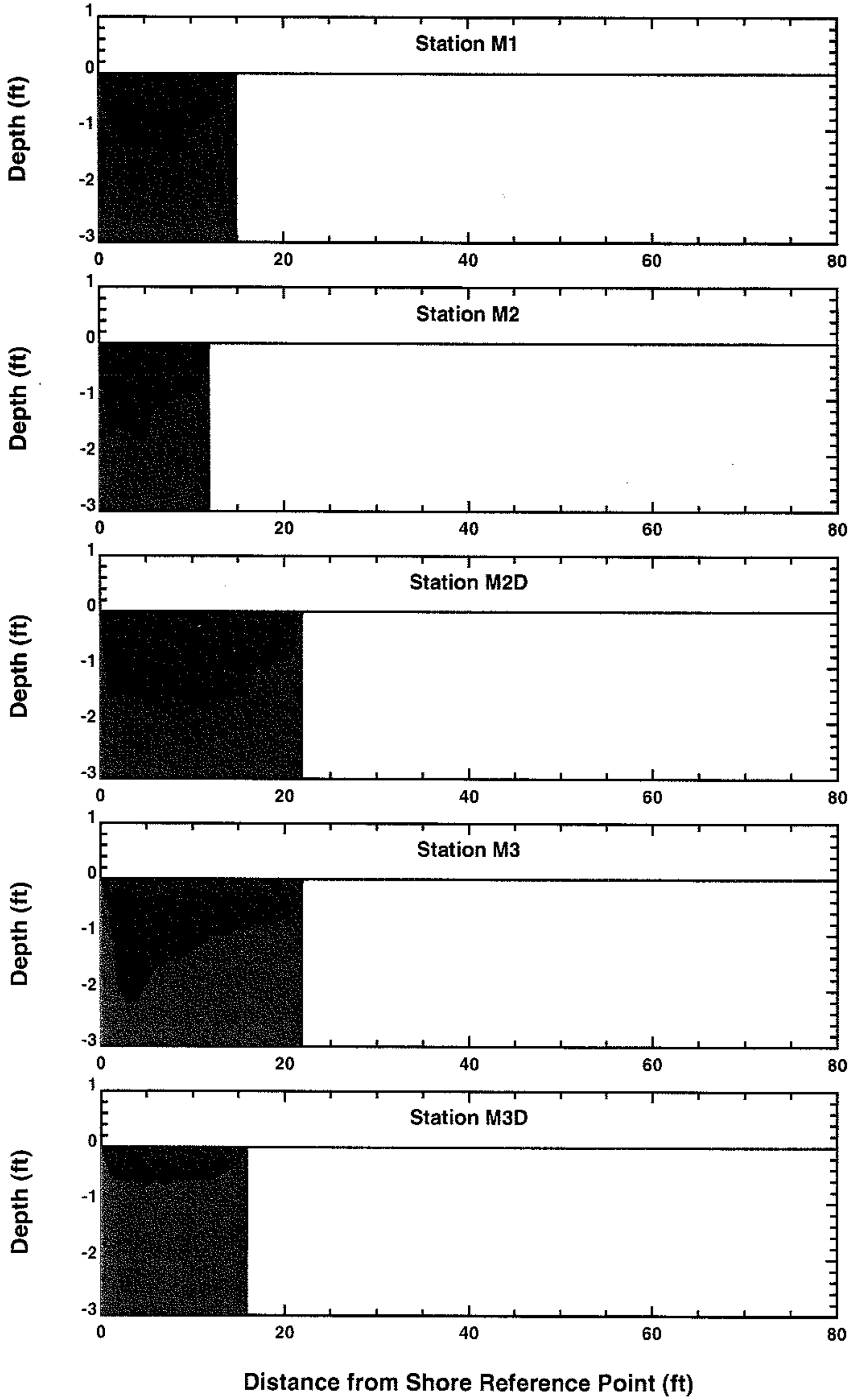


Figure 17. Opequon Creek Cross Section Data

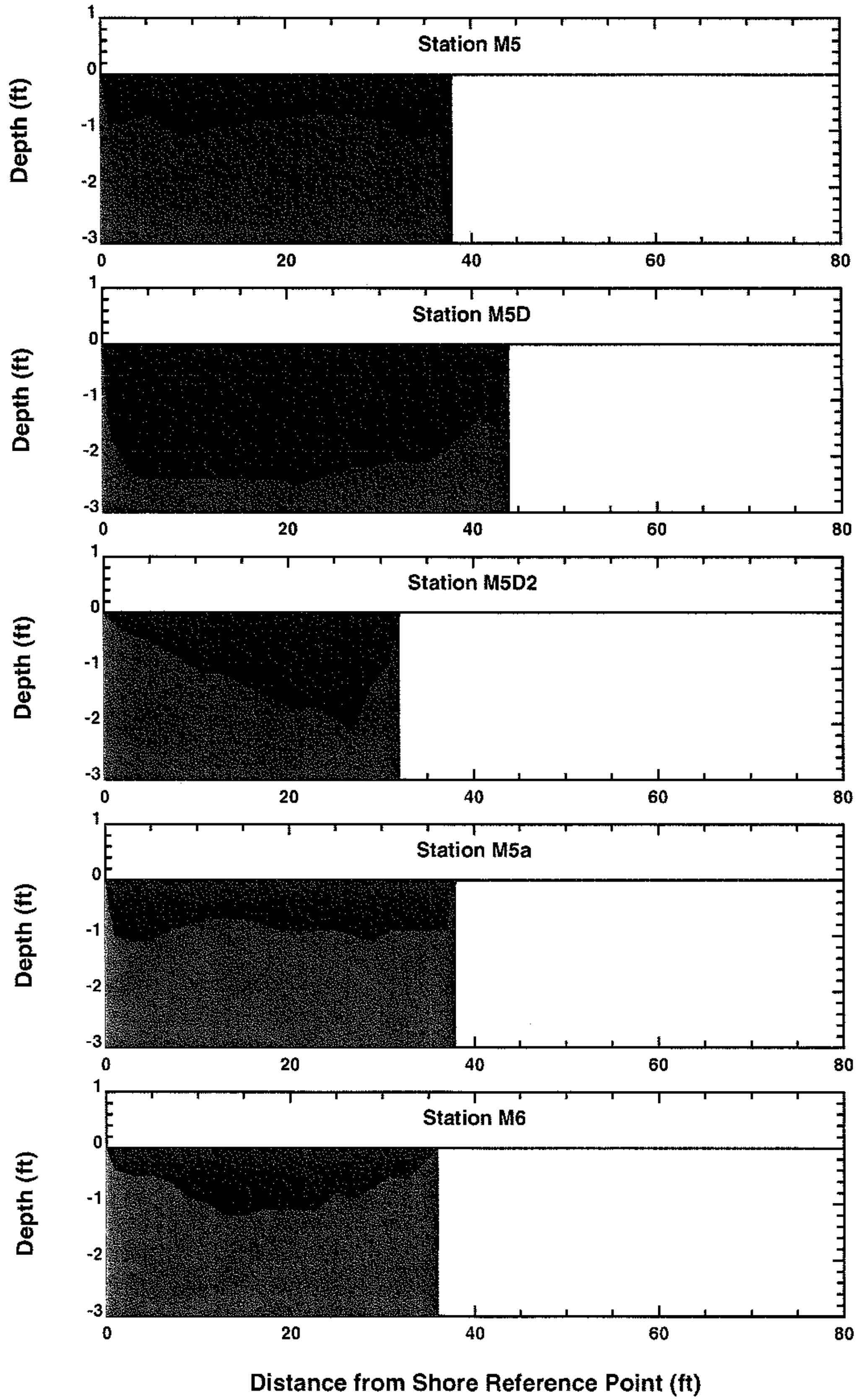


Figure 18. Opequon Creek Cross Section Data

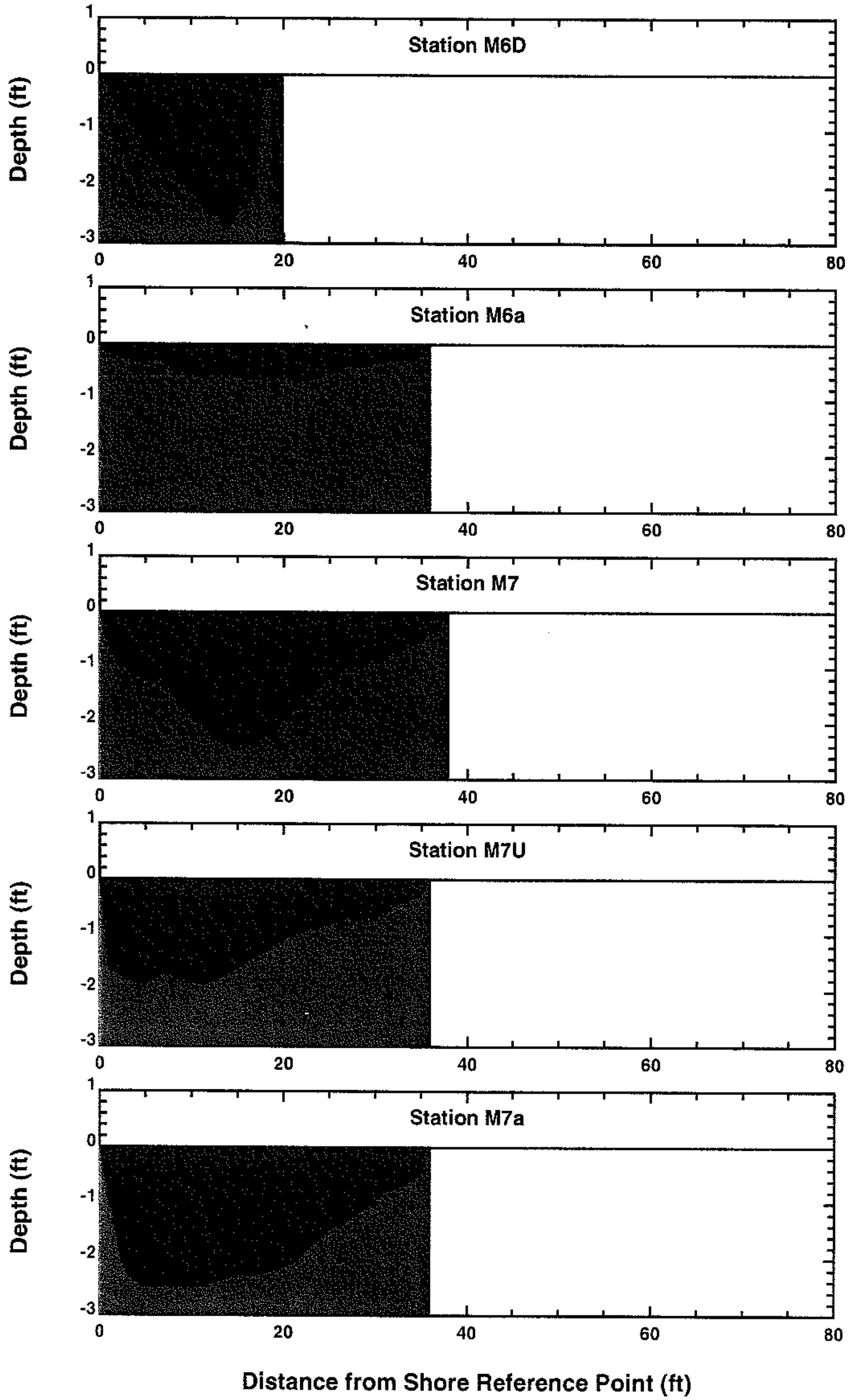
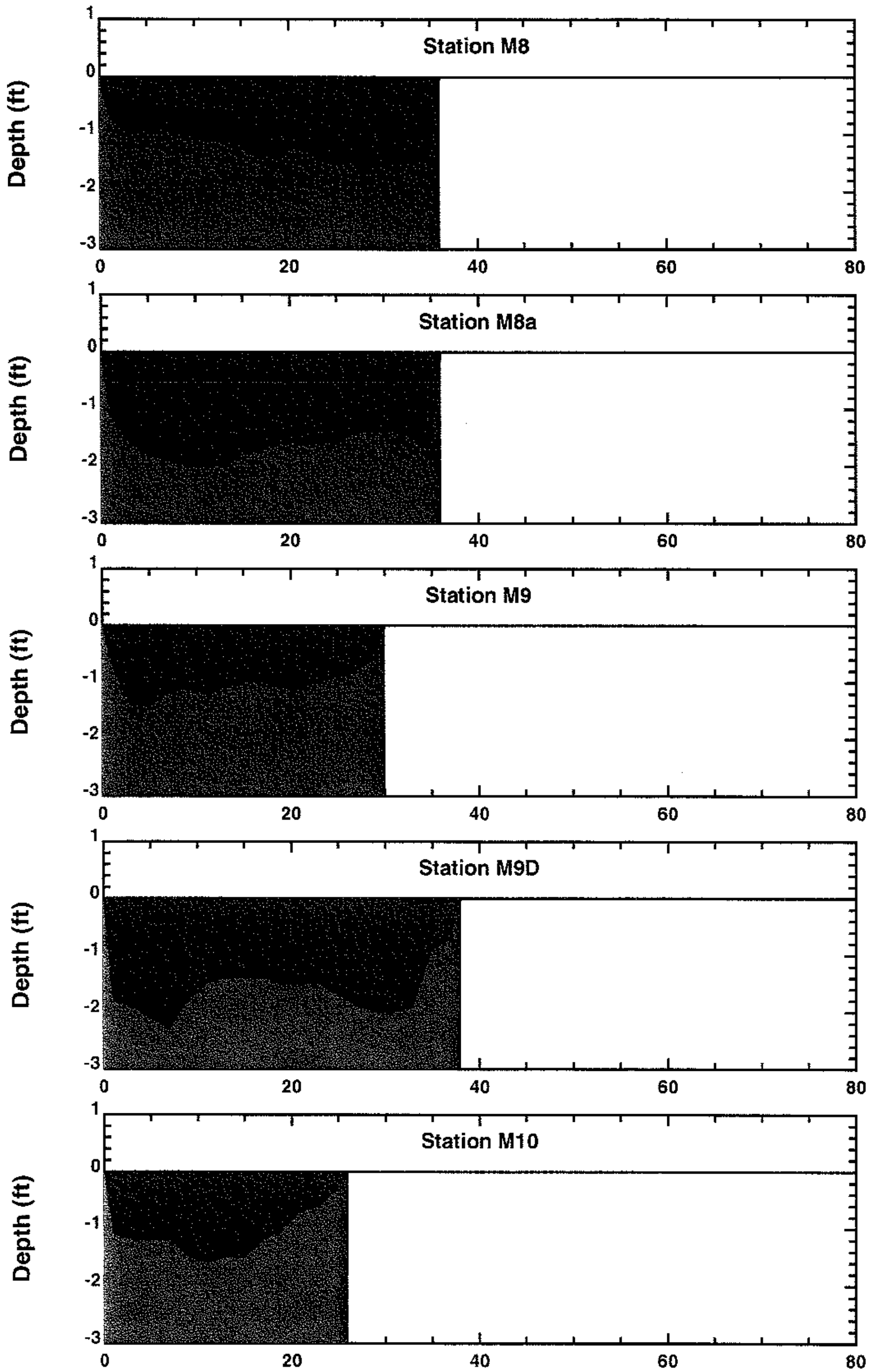


Figure 19. Opequon Creek Cross Section Data



Distance from Shore Reference Point (ft)

Figure 20. Opequon Creek Cross Section Data

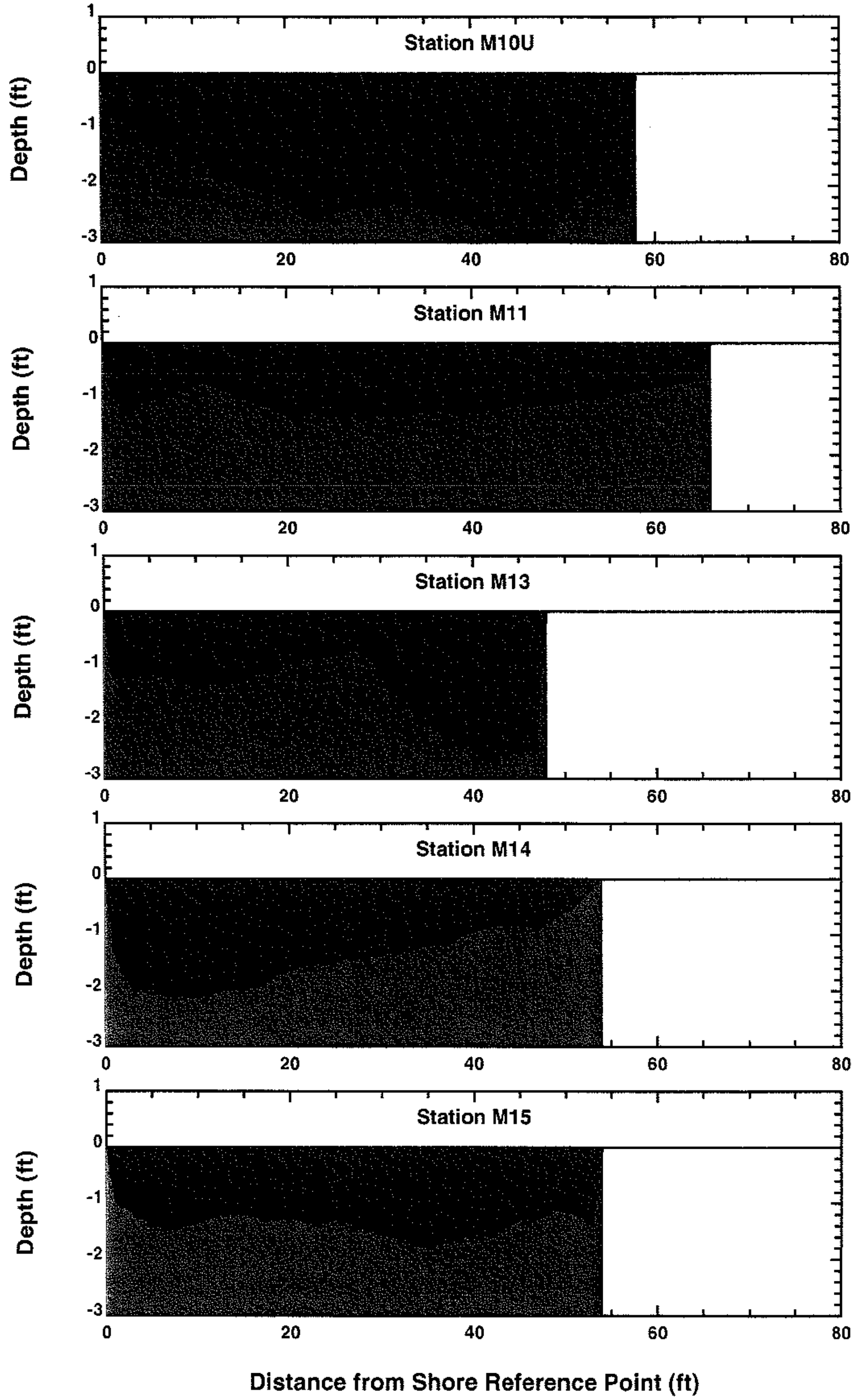


Figure 21. Opequon Creek Cross Section Data

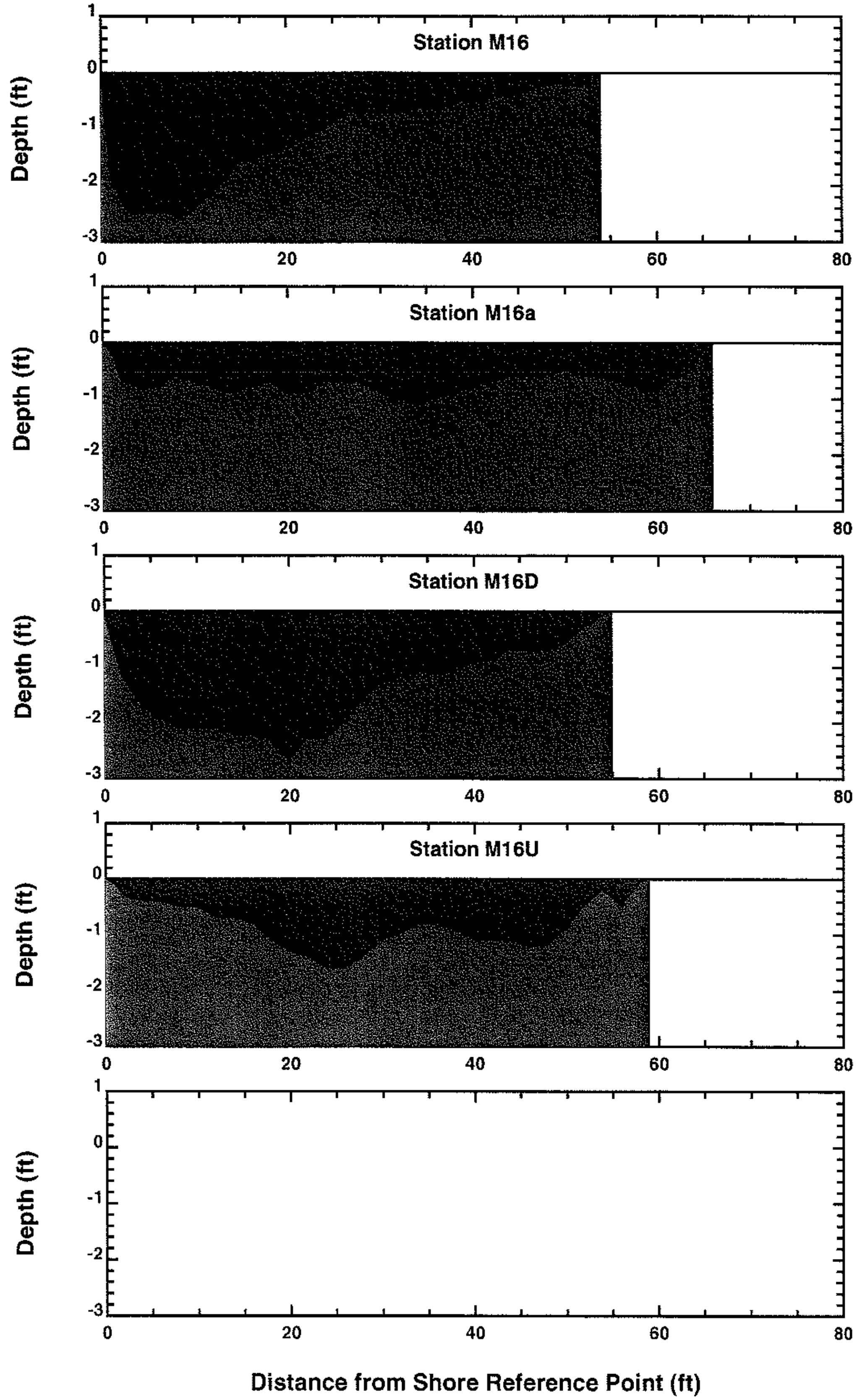


Figure 22. Opequon Creek Cross Section Data

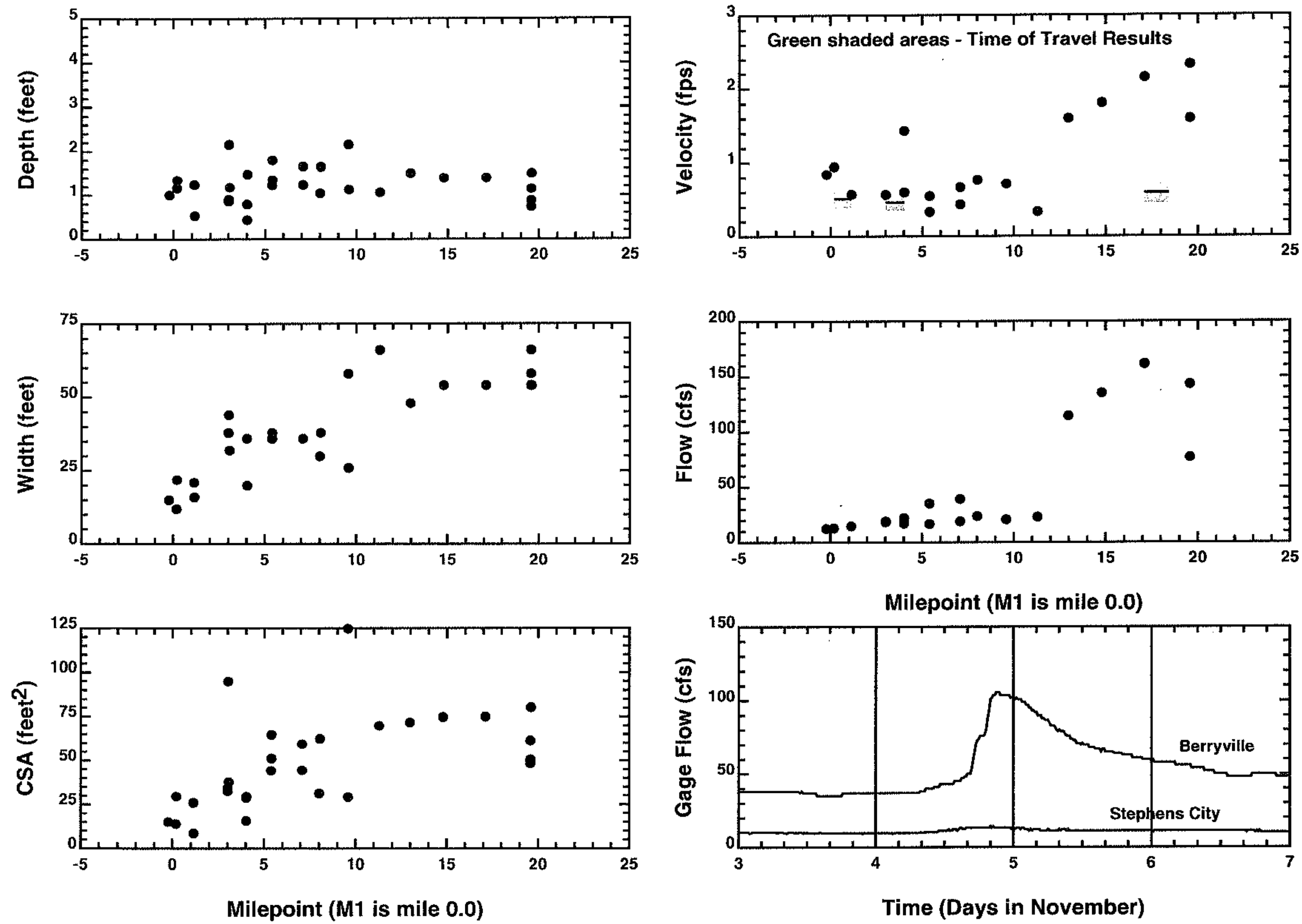


Figure 23. Opequon Creek Geometry Survey for 11/3-6/2004

measured flows at the USGS Berryville gage will be considered accurate with the calculated flows probably accurate to within +/-10-20%.

Measured creek depths during the geometry survey ranged from 0.4-2.2 feet with the shallower depths occurring upstream. Similarly, measured creek widths increased in the downstream direction and ranged from 12-66 feet. The measured cross-sectional area ranged from 8-80 square feet, velocities ranged from 0.3-2.3 feet/second (fps) and flows ranged from 12-162 cubic feet/second (cfs). In order to develop velocity and depth relationships to flow, data collected at the same station on different dates (i.e., different flows) were used to estimate the exponent in the flow relationships. These velocity and depth relationships to flow are represented with the following equations:

$$U = aQ^b \qquad H = cQ^d \qquad W = eQ^f \tag{2}$$

where:

Q = flow (cfs);

U = velocity (fps);

H = depth (ft);

W = width (ft); and

b + d + f = 1.

In a rectangular channel with depths much less than the width, the exponent for velocity can be shown to equal 0.4 and for depth 0.6 assuming a constant width. Based on the creek data collected, the velocity exponent was estimated to be 0.6. Assuming a width exponent of 0.1 and following the requirement that b + d + f = 1, the depth exponent will equal 0.3. These exponents were used to determine the velocity and depth constants (a and c) based on the data and then used to assign the geometry as a function of flow in the DIURNAL model.

2.5 TIME OF TRAVEL

The time of travel study was accomplished by injecting a conservative substance (sodium bromide) into the creek and then sampling at two downstream locations to determine instream sodium bromide profiles. By determining the center of mass in the two sodium bromide profiles, the travel time between these two points coupled with the distance between the two sampling locations were used to calculate the velocity between the two stations. Figure 24 presents the sodium bromide profiles for three reaches: M2+ to M3 (sampled 11/6 PM), M5+ to M6 (sampled 11/6 AM) and M15+ to M15a (sampled 11/3). The center of mass is presented in these figures as

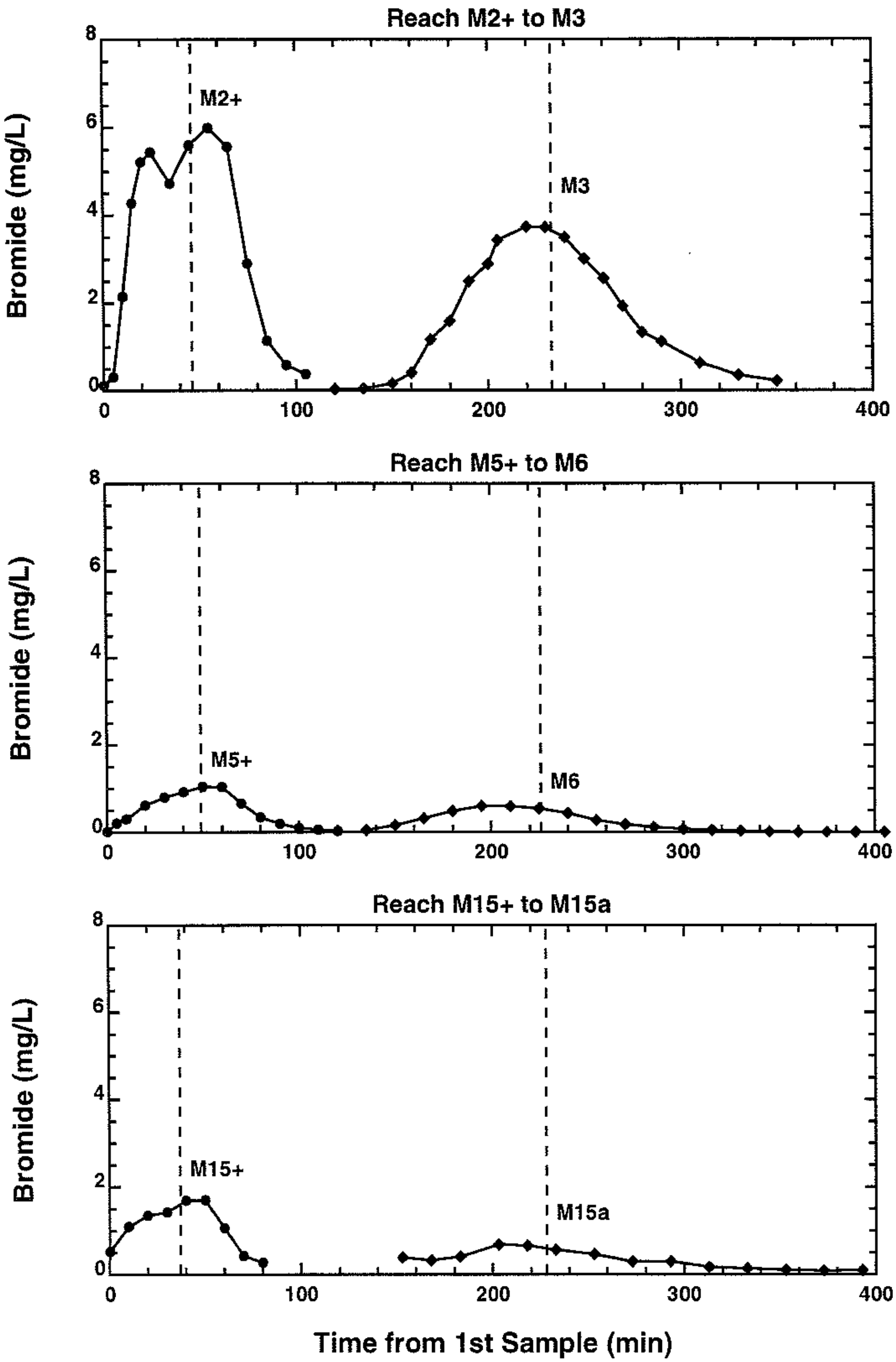


Figure 24. Time of Travel Study Bromide Profiles

the vertical dashed lines and the results in each reach are presented in Table 2 along with the creek flows as calculated from the total mass injected in the creek and the measured mass in the creek at each station. In addition, the velocities calculated from the sodium bromide data are presented in Figure 23 with the solid horizontal line representing the calculated velocity and the green shaded region representing +/- 25% of the calculated velocity.

The velocities calculated for the two upstream reaches (M2+ to M3 and M5+ to M6) based on the bromide data compare very well with the measured velocities in these areas since the creek flow conditions during each were similar. For the downstream reach (M15+ to M15a) the calculated velocity (from the bromide data) is less than the measured velocity but the flow was greater during the geometry survey when the velocities were measured and was highly variable due to the rain event. In general, the time of travel results compare well with the measured velocity data and will be used in conjunction with the geometry information to setup the DIURNAL model.

Table 2. Time of Travel Study Results

Station	Center of Mass (minutes)	Distance (miles)	Velocity (fps)	Calculated Flow (cfs)
M2+	46	1.09	0.51	17-23 (11/6/04 PM)
M3	233			
M5+	49	0.93	0.49	70-81 (11/6/04 AM)
M6	226			
M15+	37	1.28	0.57	59-91 (11/3/04)
M15a	228			

SECTION 3

DIURNAL MODEL

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DIURNAL MODEL

The DIURNAL water quality model, a model developed by Hydroscience, Inc. and upgraded by HydroQual, was chosen to represent Opequon Creek since it contains the necessary structure to simulate diurnal variation of DO in addition to the various parameters of concern (i.e., CBOD and nitrogen). This model contains the physical and biochemical reactions required for the analysis of water quality in Opequon Creek and the following section describes the mathematical model DIURNAL. In addition, the DIURNAL model was used to complete water quality modeling for the OWRF (HydroQual, 1997) and for permitting with VDEQ. The calibrated DIURNAL model of Opequon Creek presented in this report will be a valuable tool for continued permitting of the PMWWTF (permit reopening) and the OWRF (permit reapplication). Besides being applicable for the PMWWTF and OWRF discharges, the model will also include the discharge from the County Landfill that enters the creek approximately 4 miles upstream from the OWRF. This will be useful to assist in determining water quality impacts associated with the County Landfill discharge as they are now permitted to discharge during low-flow creek conditions.

3.1 OVERVIEW

DIURNAL is a one-dimensional receiving water quality model. The model includes the physical processes of dilution and advection and simulates receiving water quality changes in DO and other water quality parameters. Coupled chemical reactions can be simulated, such as the interactions between DO and carbonaceous biochemical oxygen demand (CBOD), the nitrogen series and simple phosphorus kinetics. One of the unique functions of DIURNAL is the ability to simulate diurnal photosynthetic fluctuations in DO during periodic steady-state conditions.

The DIURNAL model can be applied to streams and rivers under one-dimensional, periodic steady-state conditions. It allows a stream length to be analyzed with any number of functional segments. The number of segments is dependent upon the frequency of changes of river characteristics, tributary and waste discharge locations and resolution desired. Sources and sinks of DO considered in the model include atmospheric reaeration, CBOD, nitrogenous biochemical oxygen demand (NBOD), benthic oxygen demand, photosynthesis and respiration. The water quality parameters that may be simulated are:

1. DO;
2. CBOD;
3. Organic nitrogen;
4. Ammonia nitrogen;

5. Nitrite plus nitrate nitrogen;
6. Phosphorus (simple 1st order kinetics); and
7. One conservative substance.

The solution analysis for DO is an extension of the technique based on the continuity equation, which includes the diurnal time-variable effect of photosynthetic oxygen production. The analysis considers temporal as well as spatial distributions. The periodic extension of the photosynthetic oxygen production is expressed as a Fourier series.

3.2 MODEL THEORY

In natural systems, the DO concentration of a river is dependent on the physical characteristics of the river, wasteload inputs (point and nonpoint source) into the river and instream biological and chemical activities. Dilution and advection reduce the concentration of pollutants and transport the pollutants downstream. Natural biological activity in the aquatic environment results in the reduction of organic carbonaceous and nitrogenous compounds to stable end products and, in the process, the DO of the river water is utilized. Alternatively, atmospheric reaeration and photosynthetic activity of aquatic plants raise the DO concentration in the river. After a wasteload is discharged to an aquatic system, biochemical oxidation generally proceeds in two stages: carbonaceous oxidation and nitrogenous oxidation. These reaction rates are approximated mathematically by first order kinetic equations in DIURNAL.

Aquatic plants such as phytoplankton, periphyton and rooted aquatic plants may serve as both sources and sinks of DO. During daylight hours, these plants utilize solar energy in the photosynthetic process, release DO to the water, and at the same time consume DO for respiration. During the night in the absence of sunlight, the photosynthetic process ceases. However, the plants continue to remove oxygen from the system for respiration. The activity of the plants is affected by factors such as sunlight intensity, depth of light penetration, availability of nutrients and water temperature. Bacterial oxidation of organic matter (carbonaceous and nitrogenous) typically produces a longitudinal distribution of DO deficit. Sources of the organic matter include natural background (plant material, etc.), nonpoint sources (runoff from farms, developed areas, etc.), and point source (wastewater treatment plants, etc.). Attached or unattached aquatic plants can cause a diurnal fluctuation of DO.

3.2.1 Dissolved Oxygen

In DIURNAL, the equation for the longitudinal distribution of DO is developed by a mass balance employing the continuity equation. The specific form of the equation for a given river is determined by the hydraulic and geomorphological characteristics of the river channel and drainage basin, and the various physical, chemical and biological characteristics of the aquatic environment and wastewater discharges. Neglecting dispersions terms, the mass balance differential equation takes on the following form for the concentration of DO:

$$\frac{\partial c}{\partial t} = -\frac{Q}{A}\frac{\partial c}{\partial x} + K_a(c_s - c) - K_d\, L(x) - K_n\, N_2(x) + P(x,t) - R(x) - S(x) \tag{3}$$

The meanings of the various symbols are given in Table 3. Sources of DO, as shown above, include atmospheric reaeration, photosynthetic contribution from aquatic plants and incoming flow. Sinks include respiration by bacteria, rooted vegetation and algal respiration (phytoplankton and/or periphyton). Bacterial respiration (sediment oxygen demand, SOD) of the benthic community is assigned as a separate sink and respiration of the aquatic plants is combined as one term. DO saturation is calculated in DIURNAL as a function of the temperature and elevation above mean sea level using the saturation equation from Standard Methods for the Examination of Water and Wastewater.

Algal photosynthetic activity only takes place during daylight hours and varies with relation to light intensity. Therefore, the temporal form of photosynthesis is represented by a half-cycle sine wave:

$$\begin{aligned} P(t) &= P_m \sin\frac{\pi}{p}(t - t_s) \quad && when\ t_s \le t \le t_s + p \\ P(t) &= 0 && when\ t_s + p \le t \le t_s + 1 \end{aligned} \tag{4}$$

This function is assumed to repeat periodically on a daily cycle as a function of the maximum photosynthesis (P_m) occurring during the course of the daylight period (p).

3.2.2 Water Quality Parameters

Steady state equations, similar to the DO equations, are also employed for modeling other water quality parameters. The differential equation defining the ultimate CBOD distribution in a river without dispersion is defined in Equation 5. Given the level of treatment wastewater typically receives today, the amount of particulate CBOD discharged is negligible and the amount of discharged CBOD lost to settling can be very small compared to oxidation. Therefore, the CBOD removal rate, K_r is assumed to equal the CBOD oxidation rate, K_d.

Ultimate CBOD (CBODu)

$$\frac{Q}{A}\frac{\partial L}{\partial x} = -K_r\, L \tag{5}$$

Nitrogen forms are influenced by bacterial oxidation, algal uptake, hydrolysis and volatilization. Equations 6 through 9 show the basic steady-state differential equations for organic, ammonia and nitrite plus nitrate nitrogen and phosphorus, which form the basis of the analytical solution equations used in DIURNAL.

Table 3. List of Symbols Used in Diurnal

Symbol	Description
C	Concentration of DO
c_s	DO Saturation value
K_a	Reaeration coefficient
K_d	Coefficient of CBOD oxidation
Q	River flow
A	River cross sectional area
X	Downstream distance
t	Time
L(x)	Distribution of CBOD concentration
K_n	Coefficient of nitrogenous oxidation (nitrification)
$N_2(x)$	Distribution of NBOD (ammonia)
P(x,t)	Photosynthetic oxygen source
R(x)	Aquatic vegetation respiration sink
S(x)	Benthic bacterial respiration sink (SOD)
P_m	The maximum rate of photosynthetic oxygen production
t_s	Time at which the source begins
p	Fraction of the day over which the source is active
K_r	Removal rate of CBOD
$N_1(x)$	Distribution of organic nitrogen concentration
K_s	Settling velocity
H	Depth of river
K_h	Hydrolysis rate of organic nitrogen to ammonia
K_v	Volatilization rate of ammonia
S_{N2}	Uptake of ammonia by benthic algae
ALG_{N2}	Uptake of ammonia by suspended algae
S_{N3}	Uptake of nitrite and nitrate by benthic algae
ALG_{N3}	Uptake of nitrite and nitrate by suspended algae

Organic Nitrogen (OrgN)

$$\frac{Q}{A}\frac{\partial N_1}{\partial x} = -\left(\frac{K_s}{H}\right)N_1 - K_h N_1 \qquad (6)$$

Ammonia Nitrogen (NH_3)

$$\frac{Q}{A}\frac{\partial N_2}{\partial x} = K_h N_1 - K_n N_2 - K_v N_2 - S_{N_2} - ALG_{N_2} \qquad (7)$$

Nitrite + Nitrate Nitrogen (NO_2+NO_3)

$$\frac{Q}{A}\frac{\partial N_3}{\partial x} = K_n N_2 - S_{N_3} - ALG_{N_3} \qquad (8)$$

Phosphorus

$$\frac{Q}{A}\frac{\partial P}{\partial x} = -K_p P \qquad (9)$$

A number of calculations are performed within DIURNAL to develop segment parameters, which are not directly associated with the equations previously described. These calculations are used to set site-specific parameters and coefficients. All reaction rates are input to DIURNAL at 20°C and the model then adjusts each rate to its site-specific rate using Equation 10.

$$K_{temp} = K_{20}\,\theta^{(T-20)} \qquad (10)$$

where:

K_{temp} = temperature corrected rate;
K_{20} = rate at 20°C;
? = temperature correction factor; and
T = ambient temperature in river.

Correction factors for each reaction rate are listed in Table 4.

Table 4. Summary of Temperature Correction Factors

Reaction Rate	Symbol	T
Hydrolysis of organic nitrogen	K_h	1.08
Nitrification of ammonia	K_n	1.08
Volatilization of ammonia	K_v	1.00
Benthic uptake of ammonia	S_{N2}	1.065
Suspended algal uptake of ammonia	ALG_{N3}	1.04
Benthic uptake of NO_2+NO_3	S_{N3}	1.065
Suspended algal uptake of NO_2+NO_3	ALG_{N3}	1.04
Removal of CBOD	K_r	1.047
Oxidation of CBOD	K_d	1.047
Reaeration of dissolved oxygen	K_a	1.024
Sediment oxygen demand	S	1.065
Maximum photosynthetic oxygen production	P_m	1.065
Respiration of algae	R	1.045

3.2.3 Physical Parameters

The physical parameters of velocity and depth for each segment are calculated as a function of flow. The following equations are utilized by DIURNAL to determine stream velocity and depth:

$$U = aQ^b \qquad H = cQ^d \tag{11}$$

where:

Q = segment flow (cfs);
U = segment velocity (ft/sec); and
H = segment depth (ft).

The exponents and coefficients can be defined from available time of travel and field geometry data. The exponents and coefficients can be set as constants for a river with relatively uniform conditions or varied for changing river geometry. For uniform conditions, the exponents can be set to zero allowing the velocities and depths to be entered directly as the coefficients.

SECTION 4

MODEL DEVELOPMENT

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MODEL DEVELOPMENT

Using the data collected in 2004, the DIURNAL model was developed to represent Opequon Creek from just upstream of the PMWWTF to approximately 26 miles downstream (ending at Mill Creek/Turkey Run near station M19). The DIURNAL model requires inputs for geometry, flow, boundary conditions (upstream and tributaries), point sources, temperature and constants. After the model inputs are assigned, model calibration is completed to develop a model that best represents the available data. This calibration process is completed in two steps. First the model is calibrated to the geometry data (depth, width, cross-sectional area, velocity and flow) based on the velocity and depth to flow relationships developed. After the geometry calibration is completed, the model is calibrated to water quality data (organic, ammonia and nitrite plus nitrate nitrogen, conductivity, CBODu and DO). The following sections describe this process and results.

4.1 GEOMETRY CALIBRATION

Using the geometry data collected, velocity and depth relationships to flow were developed for each model reach and are presented in Table 5. These relationships allow the creek geometry to change as a function of flow. In order to define incremental flow along the length of the creek and also tributary flow, the creek drainage area to each model reach and for each tributary was determined. The USGS gage near Berryville was used to prorate the measured gage flow for incremental runoff to the model reaches and for the tributaries based on the contributing drainage area. The drainage area at the USGS gage near Berryville is 57.3 square miles and the proration was completed as follows: $Q_{input} = Q_{gage} \times DA_{input}/DA_{gage}$. During this survey, the PMWWTF flow averaged 2.6 cfs (1.7 MGD) and the OWRF flow averaged 12.8 cfs (8.3 MGD). Since the geometry measurements were completed on November 4th during a rain event and an increasing hydrograph, the geometry calibration was completed at two creek flows. For the geometry measurements up to milepoint 12, a gage flow of 37 cfs was used and for the remainder of the creek a gage flow of 75 cfs was used. The resulting geometry calibration is presented in Figure 25 with the model output at 37 cfs represented as a black line and at 75 cfs as a blue line. The comparison between model output and measured data is very good and, therefore, the creek geometry is well represented in the DIURNAL model.

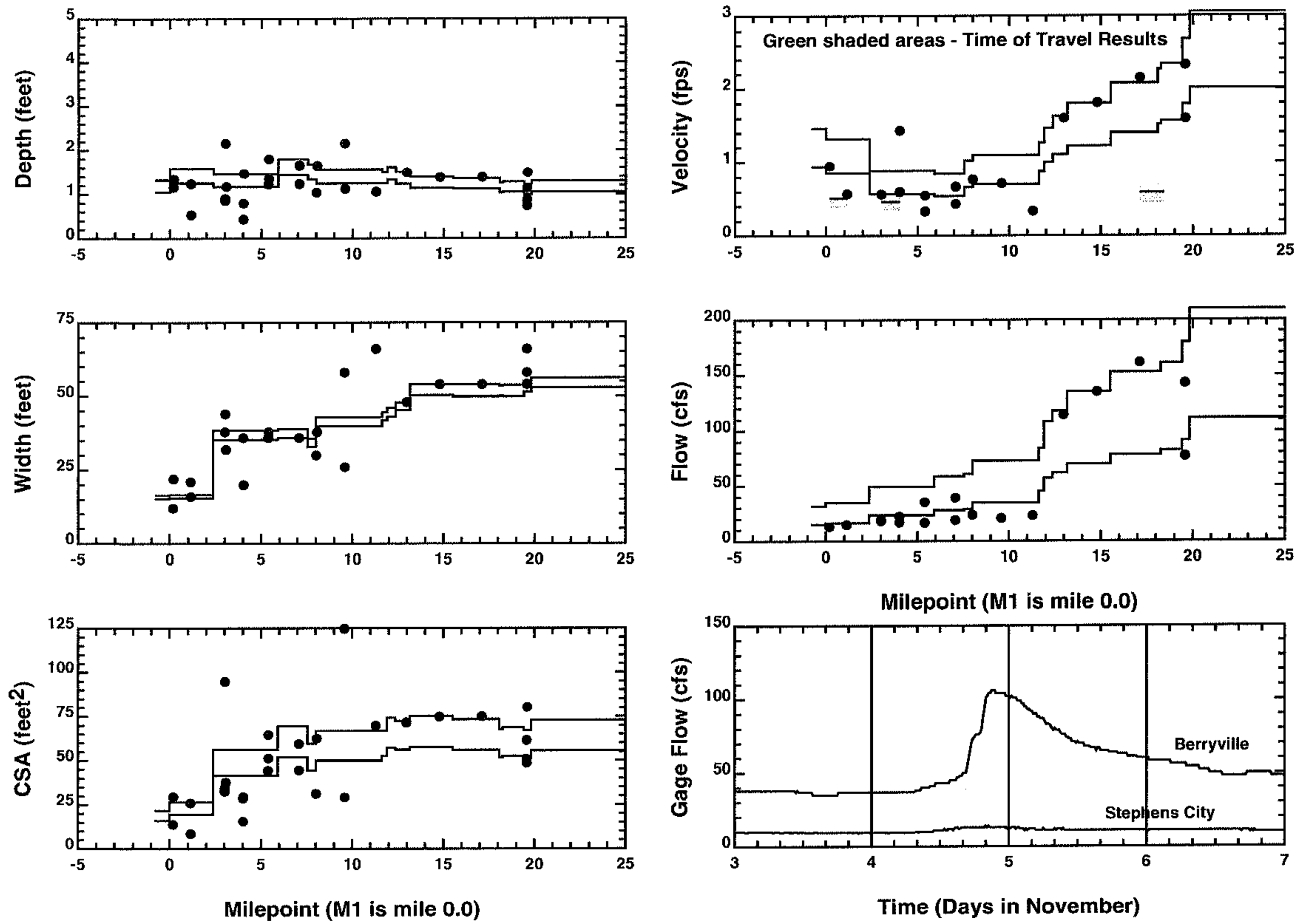

Figure 25. Opequon Creek Model Geometry Calibration for 11/3-6/2004

Table 5. Model Reach Geometry Inputs

Model Reach	Milepoints	U (fps) = a $Q^{0.6}$	H (ft) = c $Q^{0.3}$
1	-0.8 to 0.0	0.184	0.467
2	0.0 to 2.4	0.157	0.544
3	2.4 to 5.9	0.085	0.452
4	5.9 to 6.5	0.073	0.529
5	6.5 to 8.0	0.087	0.486
6	8.0 to 11.6	0.083	0.432
7	11.6 to 11.9	0.088	0.396
8	11.9 to 12.4	0.088	0.396
9	12.4 to 13.2	0.093	0.360
10	13.2 to 15.5	0.095	0.318
11	15.5 to 18.1	0.102	0.302
12	18.1 to 18.3	0.111	0.279
13	18.3 to 19.4	0.111	0.279
14	19.4 to 19.8	0.119	0.256
15	19.8 to 26.0	0.119	0.256

4.2 WATER QUALITY CALIBRATION

In order to calibrate the model to the observed water quality, inputs are required for the modeled parameters (DO, CBODu, conductivity, organic, ammonia and nitrite plus nitrate nitrogen) for the upstream boundary condition on the creek, tributaries, incremental runoff and point sources. The water quality data collected in the creek on October 13th (PM) and 14th (AM) included measurements in the tributaries and from the PMWWTF and OWRF. The PMWWTF enters the creek at MP0, the County Landfill at MP6.5 and the OWRF at MP11.6. No discharge information was available for the County Landfill so the following effluent characteristics were used based on their permitted discharge: flow of 0.23 cfs (0.15 MGD), CBODu of 75 mg/L, DO of 7 mg/L, OrgN of 5 mg/L, NH_3 of 0.001 mg/L, NO_2+NO_3 of 0.05 mg/L and conductivity of 1500 µmhos/cm. The resulting water quality model inputs are presented in Table 6 and the creek temperature averaged 13.2°C (55.8°F). During this survey, the PMWWTF flow averaged 2.1 cfs (1.4 MGD) and the OWRF flow averaged 10.3 cfs (6.6 MGD). The creek flow at the Berryville gage averaged 41 cfs and upstream at the Stephens City gage averaged 12 cfs during the two surveys and the creek geometry was calculated in the model based on the drainage areas along the creek using the velocity and depth to flow relationships presented in the previous section.

Table 6. Water Quality Model Inputs

Input	DO (mg/L)	OrgN (mg/L)	NH_3 (mg/L)	NO_2+NO_3 (mg/L)	CBODu (mg/L)	Cond. (µmhos/cm)
Upstream	10.75	0.117	0.004	2.391	1.69	545
Incr. Flow (1-3)[1]	11.56	0.226	0.005	0.108	2.21	529
Incr. Flow (4-14)[2]	9.75	0.180	0.010	1.791	1.77	606
Wrights Run	10.37	0.271	0.005	0.042	2.62	552
Buffalo Lick	12.76	0.181	0.005	0.175	1.80	507
Sulphur Spring	10.13	0.476	0.030	1.490	1.65	614
Abrams Creek	10.59	0.137	0.004	1.991	1.89	647
Redbud Run	9.79	0.075	0.005	1.791	1.88	641
Dry Marsh Run	7.91	0.061	0.006	2.175	1.53	603
Lick Run	10.35	0.150	0.006	1.509	1.90	528
PMWWTF	7.00	1.650	0.027	35.635	14.14	1500
OWRF	7.00	1.398	0.035	3.892	10.01	1250

1 – Model Reaches 1 through 3
2 – Model Reaches 4 through 14

The reaction rates in the model were based on those used in previous modeling studies of Opequon Creek (HydroQual 1997, Donohue & Associates 1992, VDEQ 2004, SWCB 1978). These rates were based on model calibration to historical data and confirmed to be acceptable based on the current model calibration work presented in this report. The required reaction rates are: CBOD oxidation, organic nitrogen hydrolysis, ammonia nitrification, atmospheric reaeration, algal maximum photosynthesis and respiration rates. There are other rates available in the DIURNAL model but these were considered to be negligible in the overall water quality dynamics due to the shallow, fast moving characteristics of the creek that are not conducive to settling and any resulting sediment related dynamics such as SOD. These other rates are organic nitrogen settling, ammonia volatilization, ammonia and nitrite plus nitrate sediment flux, ammonia and nitrite plus nitrate algal uptake, and sediment oxygen demand (SOD). Atmospheric reaeration was calculated using the

Tsivoglou-Wallace reaeration equation (USEPA, 1986), which is a function of water velocity and creek slope as described with the following equation:

$$K_a = C\,U\,S \times 86400 \frac{\text{seconds}}{\text{day}} \tag{12}$$

where:

Ka = atmospheric reaeration rate at 20°C (1/d);
C = constant dependent on flow (1/ft);
U = water velocity (fps); and
S = creek slope (ft/ft).

The constant (C) varies from 0.11 at flows less than 1 cfs to 0.048 at a flow of 100 cfs and in the model is calculated as a function of flow and velocity given the slope of the creek. In order to verify the calculated reaeration rates, the continuous DO data for November 3rd (prior to the rain event with a large diurnal DO range) was used. As mentioned previously, the shape of the daily DO curve is related to the reaeration rate. Therefore, the model was run with the calculated reaeration rates with the maximum photosynthesis (Pmax) and respiration (R) rates adjusted to match the DO data. Figures 26 and 27 present the comparison of model and data over the day with the solid line representing the model and the dashed line the data. The hourly model results at stations M3, M6, M8, M10, M13 and M15 compare very well with the measured data, particularly the shape of the diurnal curve, which indicates that the calculated reaeration rates are represented well in the model.

The algal maximum photosynthesis (Pmax) and respiration (R) rates are required to properly calculate the observed diurnal range in DO. These rates are determined by calibrating the model to the observed daily DO data (R = 0.15Pmax) and are a function of the available sunlight or cloud cover. Along with these rates the time of sunrise and length of daylight are required, which were obtained from the US Naval Observatory website (http://aa.usno.navy.mil/data/docs/RS_OneYear.html). Tables 7 and 8 present the rates used for the model calibration. Higher Pmax and R rates were required to match the November 3rd data than the October 13th-14th data because the weather conditions during the latter survey were relatively overcast.

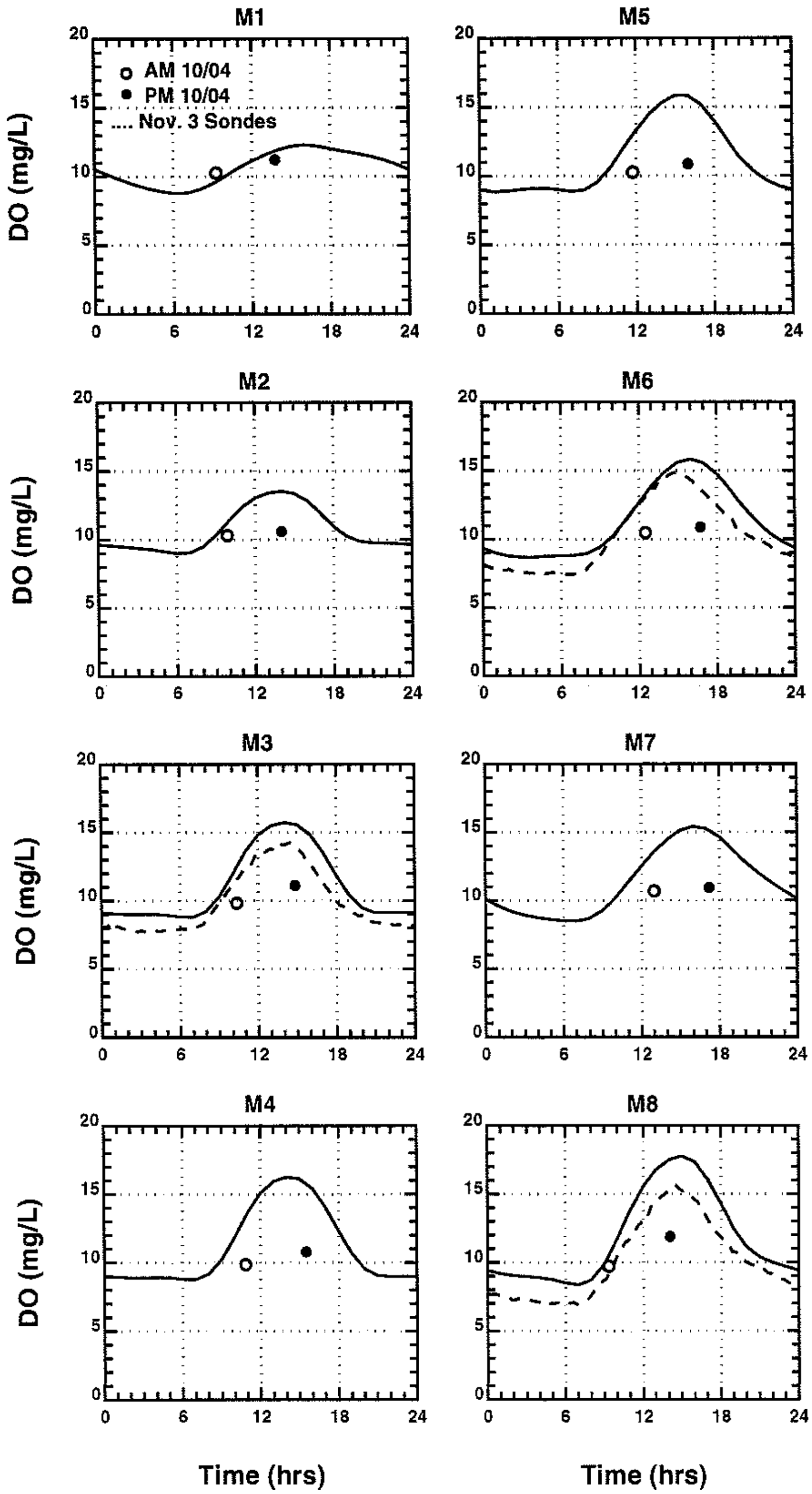

Figure 26. Opequon Creek Diurnal DO Calibration

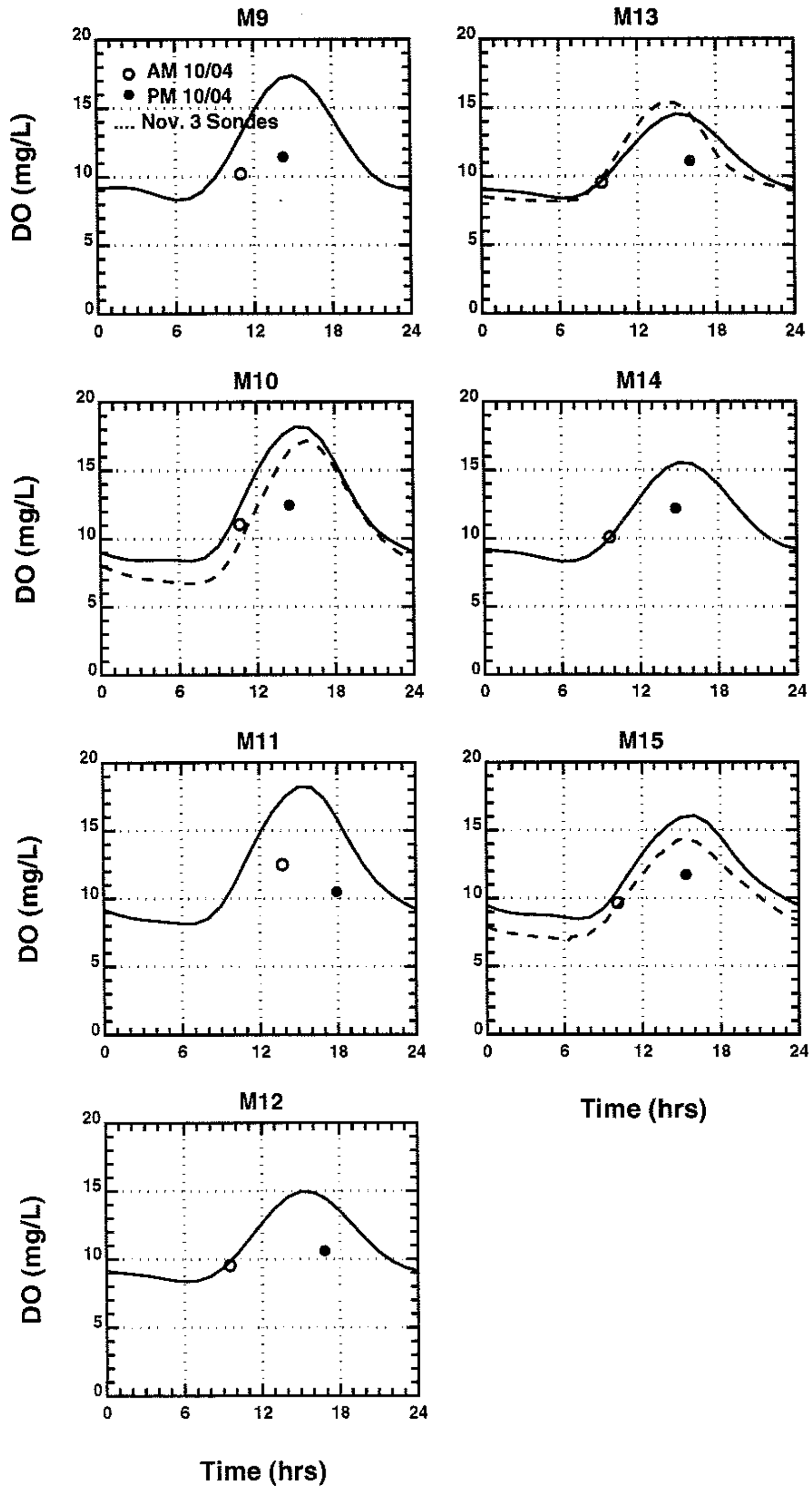

Figure 27. Opequon Creek Diurnal DO Calibration

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Table 7. DIURNAL Model Calibration Rates

Reaction Rate	Rate at 20°C (1/d)
CBOD Oxidation	0.5
OrgN Hydrolysis	0.001
NH_3 Nitrification	0.5
Reaeration Rate	4.6 – 33.8
Time of Sunrise (hrs)	7.33
Length of Daylight (hrs)	11.25

Table 8. Model Calibration Pmax and R Rates

Model Reach	10/13-14/2004		11/3/2004	
	Pmax (mg/L/d)	R (mg/L/d)	Pmax (mg/L/d)	R (mg/L/d)
1	50	7.5	100	15
2	50	7.5	200	30
3	25	3.75	75	11.25
4	50	7.5	125	18.75
5	50	7.5	175	26.25
6	50	7.5	150	22.5
7	50	7.5	100	15
8	50	7.5	100	15
9	50	7.5	100	15
10	50	7.5	100	15
11	50	7.5	100	15
12	50	7.5	100	15
13	50	7.5	100	15
14	50	7.5	100	15
15	50	7.5	100	15

Figure 28 presents the DIURNAL model calibration to the observed data on October 13th and 14th for OrgN, NH_3, NO_2+NO_3, conductivity, CBODu and DO. The unique feature of the DIURNAL model is that it calculates DO over a daily cycle (hourly) unlike the QUAL2E model. The hourly DO output from the model is presented in Figures 29 and 30 for the stations in the creek. In both figures, the solid line represents the model output and the filled symbols represent the data. The dotted lines in Figure 28 in the DO panel represent the minimum and maximum calculated DO over the day. In general, the DIURNAL model output compares very well with observed data for all parameters over the length of the creek analyzed. For the nitrogen series, the model tends to be slightly greater than the data below the OWRF for OrgN and NH_3, which may be due to some nitrogen uptake below the outfall. Also the model NO_2+NO_3 is less than the data below the County Landfill, which may indicate a high NO_2+NO_3 groundwater source or higher than estimated load from the landfill. More importantly, the model represents the measured CBODu and DO data well over the length of the creek.

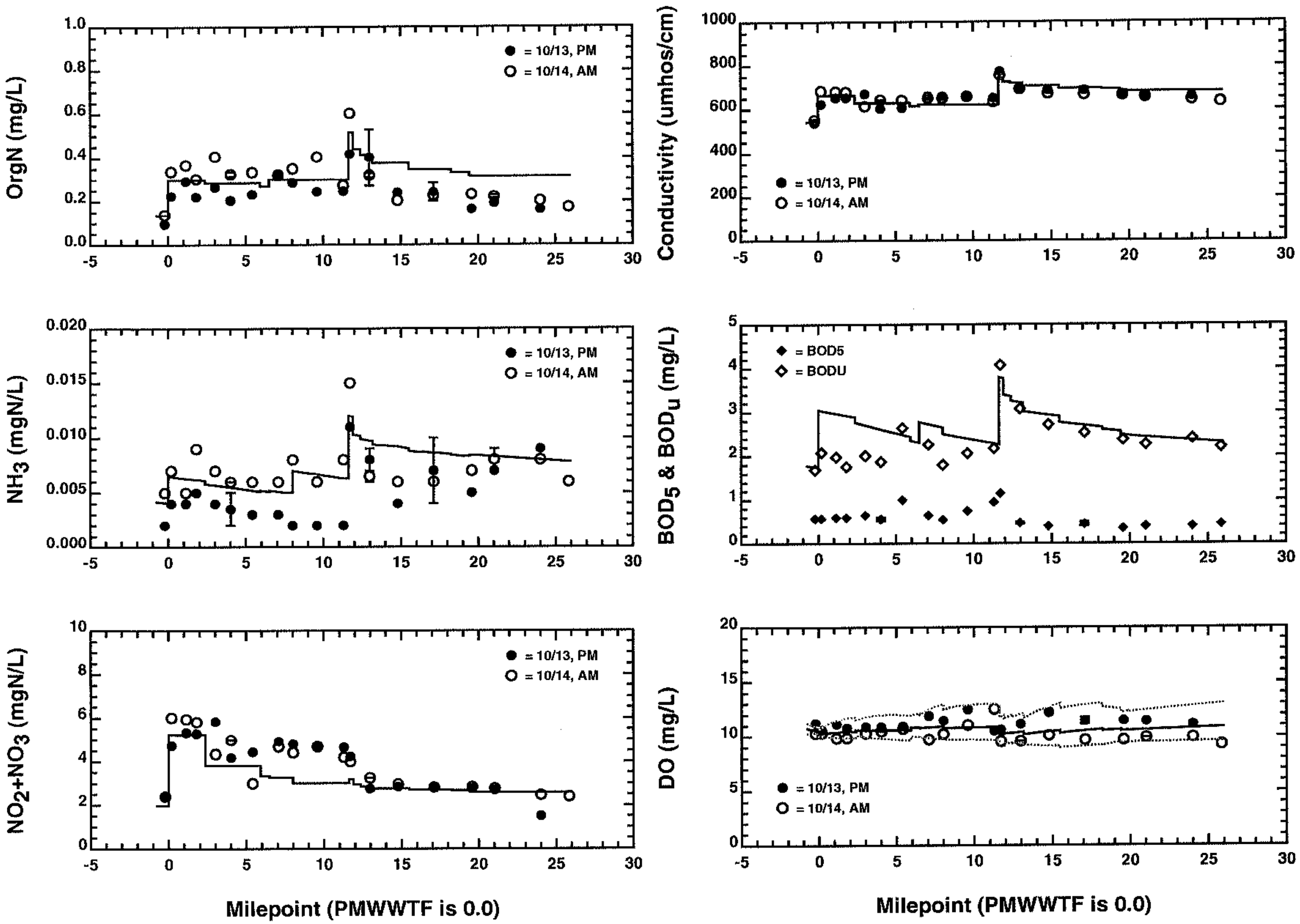

Figure 28. Opequon Creek Water Quality Data for the 10/13-14/2004 Survey

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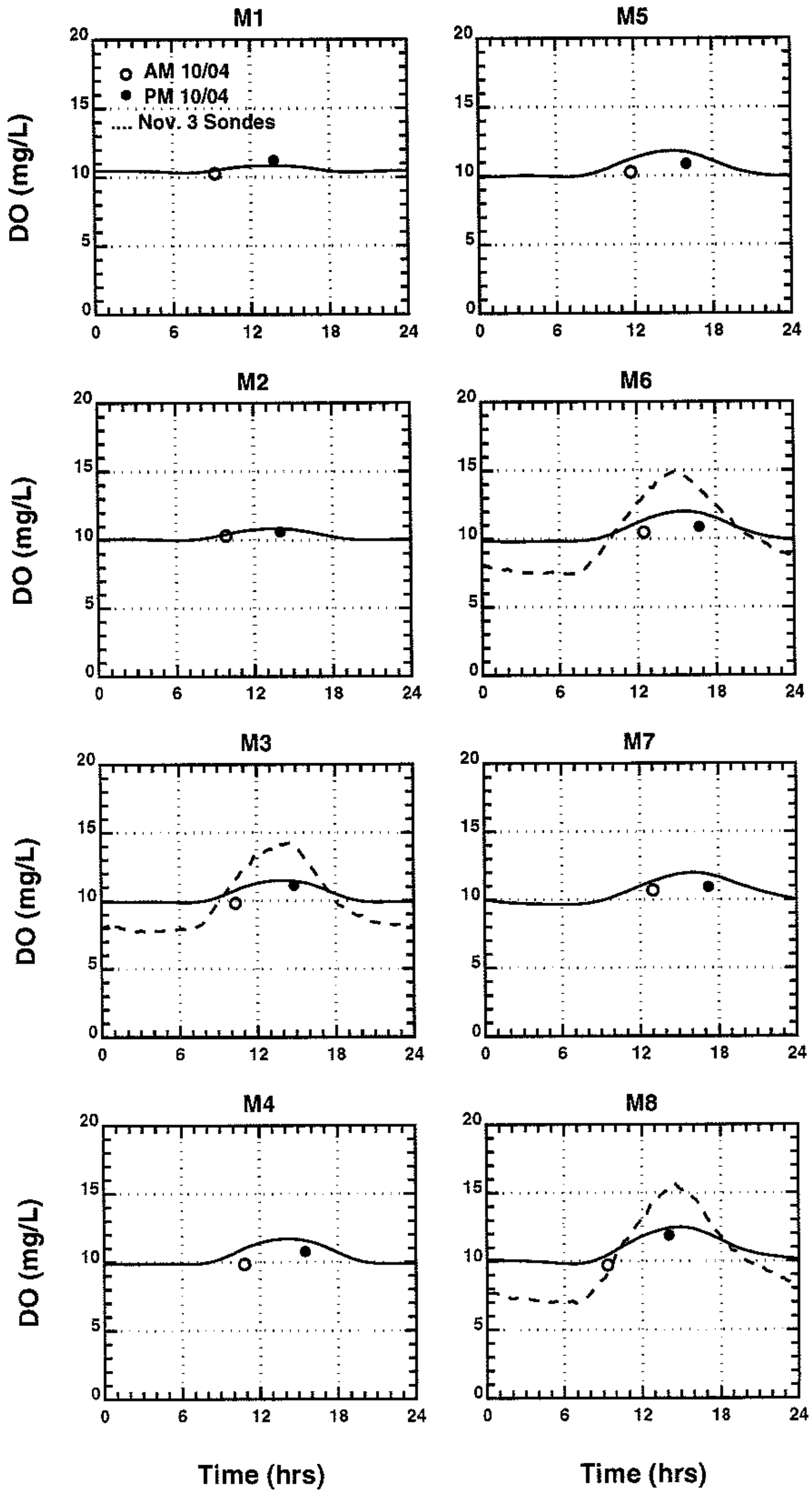

Figure 29. Opequon Creek Diurnal DO Calibration

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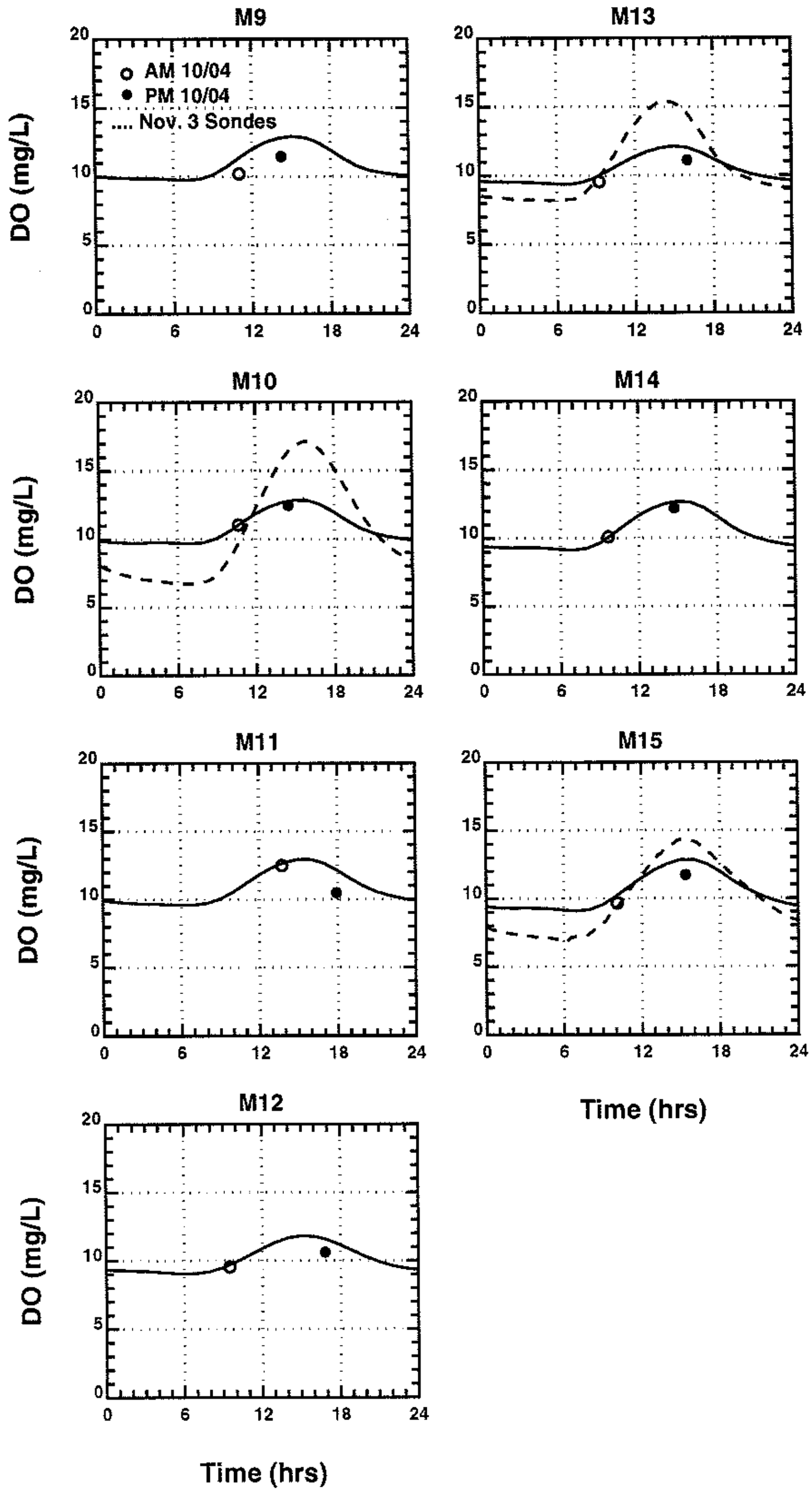

Figure 30. Opequon Creek Diurnal DO Calibration

DATE: 2/23/2005 TIME: 12:23:44

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